AN EVALUATION OF THE FIDELITY OF MOTION SIMULATORS USING A MODEL OF HUMAN DYNAMIC ORIENTATION.

Richard G. Fuller

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN EVALUATION OF THE FIDELITY
OF MOTION SIMULATORS
USING A MODEL OF
HUMAN DYNAMIC ORIENTATION

by

Richard G. Fuller

September 1977

Thesis Advisor: Lewis E. Waldeisen

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) An Evaluation of the Fidelity of Motion Simulators Using a Model of Human Dynamic Orientation	5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; September 1977
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard G. Fuller	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940	12. REPORT DATE September 1977
	13. NUMBER OF PAGES 95
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Postgraduate School Monterey, California 93940	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Motion Simulation
Vestibular Modelling
Aircraft Simulators
Simulator Fidelity

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A deterministic simulation using a model of human dynamic orientation was written to optimize the parameters of the motion base control system for a six-degree-of-freedom flight simulator. An experiment requiring pilots to rate different levels of motion fidelity during a basic flight task provided a data base for validation of the simulation. Ratings between

20. Abstract

subjects for linear, rotational, and combined motion cues were inconsistent due, in part, to the subjects' lack of experience in the F-15 aircraft and proficiency in high performance aircraft. The coefficient of concordance among subjects for the three ratings were .4483, .4835, and .5914, respectively. Comparison of simulation results with experimental data yielded positive correlations as high as .5138. Response of the simulation to changing wash-out filter parameters was investigated and found to be adaptable to experimental optimization methods.

An Evaluation of the Fidelity of Motion Simulators Using a Model of Human Dynamic Orientation

by

Richard G. Fuller
Lieutenant, United States Navy
B.S., Rensselaer Polytechnic Institute, 1968

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 1977

ABSTRACT

A deterministic simulation using a model of human dynamic orientation was written to optimize the parameters of the motion base control system for a six-degree-of-freedom flight simulator. An experiment requiring pilots to rate different levels of motion fidelity during a basic flight task provided a data base for validation of the simulation. Ratings between subjects for linear, rotational, and combined motion cues were inconsistent due, in part, to the subjects' lack of experience in the F-15 aircraft and proficiency in high performance aircraft. The coefficient of concordance among subjects for the three ratings were .4483, .4835, and .5914, respectively. Comparison of simulation results with experimental data yielded positive correlations as high as .5138. Response of the simulation to changing wash-out filter parameters was investigated and found to be adaptable to experimental optimization methods.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

Successful completion of this thesis would not have been possible without the contributions of many individuals. Particular acknowledgement is due Dr. David Nagel of the NASA Ames Research Center who provided the opportunity, encouragement, and numerous original ideas for this study. Without the constant help of both thesis advisors, the author could have strayed from the purpose on several occasions and committed numerous errors.

Special thanks are due the operators and consultants of the W. R. Church Computer Center, Naval Postgraduate School. Their expertise and special considerations contributed greatly to completion of this work. Also, the engineers, technicians, and data processors of the Computer Science Corporation (CSC) deserve many thanks for their assistance and advice.

I. BACKGROUND

A. GENERAL

The modern, complex flight simulator has assumed an expanded role in aviation research and development as well as in military and civilian training programs. In the face of the current energy crisis, manpower and budgetary cutbacks, and reduced flight operations, the Department of Defense (D.O.D.) has recognized the benefits of judiciously substituting simulator "flight" time for aircraft hours. Supplementing existing training programs with instruction in flight crew trainers has long been an effective means of training safe, professional aviators. D.O.D. has established an objective of reducing flight operations 25% by the end of Fiscal Year (FY) 1981. The Chief of Naval Operations (CNO) has recently authorized the substitution of simulator time for ten percent of total annual flight time requirements (25 percent of the annual instrument flight time). Reference 1 states the CNO's policy:

> "As additional simulators become available and more is learned on the 'transfer of learning' gained through the use of simulators, this program will be expanded."

Increased emphasis on the use of synthetic training devices has accelerated the procurement and funding of special part-task trainers such as the Navy's Air Combat Maneuvering device and Universal Night Carrier Landing Simulator. Total D.O.D. FY77 procurement funding for training devices is 298.7 million dollars as compared to 88.5

million in FY74. Research and development funding during the same period has nearly doubled [Ref. 2]. The development and deployment of modern combat aircraft today is paralleled by the production of high-fidelity weapon system trainers. Advanced weapon platforms such as the F-14, S-3A, P3-C, SH-2F, and the SH-3H have (or will) become operational concurrently with advanced, full task, motion base trainers.

The following section reviews the current "state of the art" of the flight simulator as a tool in the training environment, research and development community, and in the field of accident investigation. It references selected studies and events that demonstrate the devices' capabilities and effectiveness.

1. Training

Understanding the benefits of flight crew trainers is essential to their cost effective use within comprehensive training programs. Efficient use of simulators reduces the expense of fuel, weapons, support equipment, and manhours. It also reduces the competition for hardware between training, operational, and maintenance departments. Alloted training hours can be devoted entirely to the task at hand, eliminating time for such activities as preflight, refueling, and clearance acceptance. As well as reducing accidents, it provides a safer environment for practice of hazardous or emergency flight operations. The advanced system incorporates features such as "freezing" the problem for real-time critique, replaying the maneuver allowing the student to objectively

review it while fresh in his mind, and computation of purely objective performance measures using computer based algorithms. (See Ref. 3 and 4 for examples.)

Instruction in training devices provides better control of psychological factors such as stress and workload levels. Use of a select, limited number of experienced instructors enhances standardization of undergraduate and "fleet" pilots.

The Naval Air Training Command, in 1972, began evaluation of a computer generated imagery system which complemented the existing TA-4 2F-90 flight simulator. The device provided visual scenarios such as aircraft carrier landings, a bombing range complete with scoring system, and carrier catapult launches. The resultant success in the Familiarization Stage of the advanced student flight training syllabus was expressed in the following statements [Ref. 5]:

> "The major area of benefit has been the practice provided in VFR procedures and techniques. The addition of a carrier visual presentation has made student instruction in CQ [carrier qualification] possible with much the same results as those experienced in FAM stage. The real benefit of the simulator however has proven to be in the weapons delivery phase of the syllabus. Bomb instructors have noticed a significant improvement in the students' ability to fly the pattern and develop the principles of bombing as a result of incorporating simulator flights into the weapons stage. ...After a short period of instruction, it was evident that students who had had several hops in the simulator were, to a significant degree, outperforming those who had not."

> "The real key to the value of the simulation is the hit-spotting program which provides the instructor with real time readouts of release altitude, release mach number, dive angle, and hit position. ...The instructor may also introduce any of a multitude of factors affecting mission completion including adverse weather, aircraft malfunctions, variable winds and many others affecting flight safety. ...The system has enabled the

instructors to provide the student aviator with a high degree of realism and a method of evaluation which, until now, has been unavailable even in the aircraft."

2. Research and Development

The use of cockpit simulators in the research, development, test, and evaluation phases of new aircraft allows the aeronautical engineer to develop flight systems and procedures without use of the prototype aircraft. Concurrent development of mockups provides for efficient aircrew station design and analysis from a system and human factors standpoint. Design of displays and controls is simplified with construction of full-scale prototype crew stations. Realistic, motion base simulators, driven by mathematical models derived from wind tunnel testing, allow test pilots to optimize aircraft performance capabilities and "handling qualities" specific to the mission.

Development of the U.S. Air Force/Boeing Advanced Medium STOL (short takeoff and landing) Transport was aided extensively by the use of Boeing fixed-base and NASA motion base flight simulators. The following advanced aircraft design concepts were evaluated on the devices before incorporation into the prototypes [Ref. 6].

- engine bleed air for leading edge flap boundary layer control (BLC)
- redundant mechanical and electrical flight controls
- aerial delivery procedures
- satisfactory handling qualities and criteria for engine-out STOL approaches

- "conventional" piloting techniques for STOL speed and flight path control.

An added benefit, recently used in the development of the F-14, is the capability to design, evaluate, and optimize specialized subsystems. The Automatic Carrier Landing System (ACLS) of the F-14 "TOMCAT" was developed using a 3-degree of freedom (pitch, roll, and heave) NASA cockpit simulator [Ref. 7]. After "proper validation" of the flight dynamics, optimization of the parameters of the ACLS's three main components began. Use of simulated flights in lieu of aircraft flights yielded "significant increases and flexibility in the number of combinations [of parameters] that can be examined for aircraft subsystems which have many parameters to specify." Other advantages of the program were soon realized:

> "1. Allowed seven iterations of SPN-42 [shipboard guidance equipment] parameter values to be examined in two to three days instead of the normal two to three weeks and several flights.
>
> 2. Provided qualitative predictions of pilot comments on closed loop ACLS control characteristics and quantitative prediction of performance statistics, pilot AQR (ACLS Quality Rating), and to a lesser extent, open and closed loop frequency responses.
>
> 3. Saved \$120,000 and \$150,000 and approximately six months in the SPN-42 optimization phase of ACLS development."

> "The impact of this new T&E capability is indicated by the inclusion of specific periods of simulator utilization in the ACLS development plan for the S-3A airplane. Similar utilization will likely be specified for the F-18 airplane. In addition, the same NASA-Ames Research Center R&D simulator used for the F-14A has been reprogrammed to attack long standing ACLS problems of the A-7E and A-6 aircraft."

3. Accident Investigation

Cockpit simulators have proven to be an indispensible tool for reconstruction of pre-accident histories. The present capability to use data from inflight recorders to derive flight profiles, environmental conditions, and signals with which to "drive" simulators is impressive. Current digital recorders can record up to 64 flight parameters per second. However considerable re-formatting of the data is then required in order that simulators can use the data directly. A current NASA program is in pursuit of the capability to recreate pre-accident flight conditions using information from flight recorders, voice recorder data, radar tracks, and meteorological data.

The investigation into the crash of an Eastern Airlines B-727 in June, 1974, by the National Transportation Safety Board included evaluation of the wind shear and downdraft activity encountered by the aircraft [Ref. 8]. Fourteen experienced pilots flew a total of 54 approaches in a fixed-base B-727 cockpit simulator programmed with four different hypothesized wind models. Even with an à priori knowledge of the type and severity of the storm activity, 18 flights "crashed", while only five flights resulted in placement of the aircraft near the runway threshold. Subsequently constructed flight profiles (airspeed and altitude traces) closely resembled those from the B-727's flight recorder, validating, to some extent, the wind shear models. At the time of the crash, the flight crew was thought to be

attempting visual contact with the runway environment. Seven of ten pilots who commented following the tests felt that their efforts to "go visual" at decision height delayed their recognition of the sink rate produced by the wind shear and downdraft conditions.

A committee, chaired by the Director of Aviation Safety Programs, Naval Postgraduate School, was formed in 1975 to investigate present use and potential of flight simulators in aircraft accident prevention and investigation. Representatives from government, NASA, and the airline industry recommended further research into the use of existing inertial navigation equipment to record available flight accelerations in a form adaptable to simulators [Ref. 9]. The committee offered these recommendations:

> "Crash-protected digital flight recorders should be installed in high valued aircraft (with inertial navigators). There should be a unified effort to develop and implement standardized data collection and processing procedures which would facilitate recreation of accident/incident conditions in flight simulators. Voice recorders, especially on multi-crew aircraft, should also be considered."

B. NATURE OF THE PROBLEM

1. Pilot-Simulator Feedback Loop

While accomplishing a certain task in a flight simulator, the pilot responds to various visual, kinesthetic, audio, and vestibular feedback cues (see Fig. 1). Feedback may be classified as either "intrinsic" (e.g., control "feel" or amplitude of movement necessary in the operation of a control) or "extrinsic" (the consequences or results of

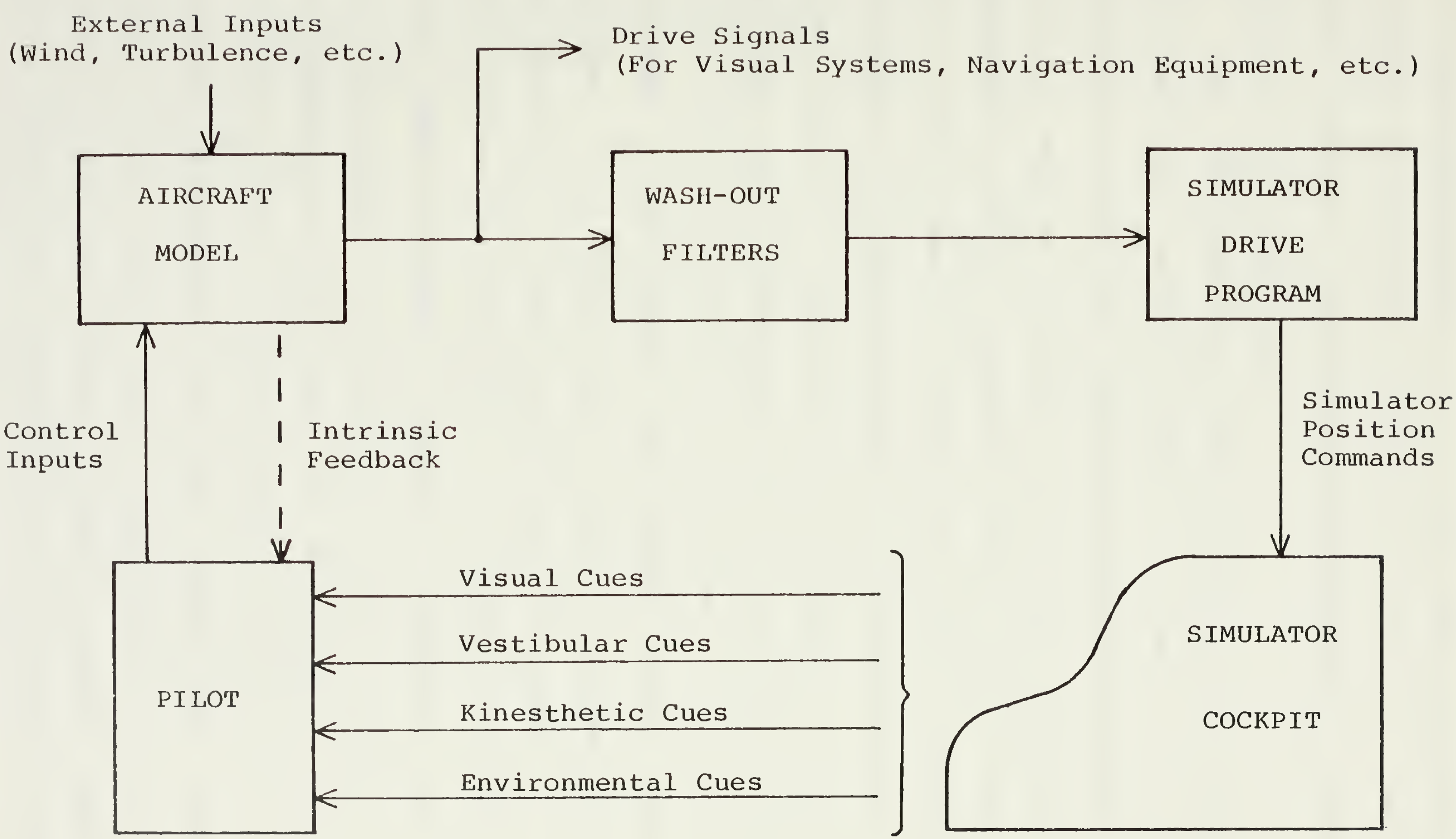


Figure 1: Pilot-Simulator Feedback Loop

control operation). The problem encountered by a designer is one of cost-effectiveness, i.e., which cues are necessary and what degree of fidelity is required of each cue to ensure a positive transfer of training at the particular stage of learning for the given task.

The requirement for motion fidelity in a flight simulator has been an ongoing question for years. It cannot be debated that motion cues simulating airframe buffeting as well as in response to flight control inputs adds greatly to psychological fidelity, especially during early stages of training. Many research studies have compared fixed-base and motion base simulators measuring pilot performance, learning rates, and subjective pilot responses. Where motion cues play an important role in the pilot's feedback loop, the addition of motion cues creates a significant improvement in performance. For example, during instrument approaches, the inherent lag in cockpit instrumentation forces the pilot to rely on the vestibular sense to a higher degree. (A possible argument for fixed-base instrument training, where the pilot is forced to depend on artificial cockpit references). During visual carrier landings, the first sensation of rapid glide path deviation is typically through the vestibular and kinesthetic sensors, quickly confirmed by movement of the visual landing aid. Another scenario in which motion cues are important to the pilot is low-level, high speed terrain following flights. Where motion tends to degrade pilot performance, the addition of these cues allows a quicker transfer of learning to the aircraft.

2. Physiology of Motion Detection

Man perceives the sensation of motion through three main sensors. The eyes view the changing world around him. The kinesthetic sensors within his body respond to the rate of change of movement of his body and its members. The semicircular canals and otolith organs are the main components of the highly specialized vestibular system of the inner ear. The inner ear canals react to changes in rotational velocity, i.e., angular acceleration. The utricles and saccules of the otolith system respond to linear accelerations.

The present intent is not to analyze in depth the physiology of the vestibular system, but to review the motion to which the organs respond. (A more comprehensive review of vestibular physiology and its function is available in Ref. 10.)

The fluid-filled semicircular canals form a roughly orthogonal set of sensors in each inner ear. The endolymph fluid lags behind the movement of the canal walls when the head undergoes rotation. This relative motion tends to displace the cupula which obstructs an expanded portion of the canal called the ampulla. Deflection of the cupula excites sensory hair cells at its base causing an increase in the firing rate of the afferent nerve fibers. Orientation of the canals is such that those on the left side of the head are coplanar with those on the right side of the head, sensing motion about the same axes, but in the opposite direction, thereby acting as a single unit. It can be

assumed that the central nervous system responds to the difference of their respective afferent responses.

The otolith system of the inner ear is comprised of two utricles and two saccules. Each is a mass of calcium carbonate crystals suspended by sensory hair cells. Linear accelerations tend to displace the mass exciting the afferent nerve endings at the base of the hair cells. The utricle organs are oriented so as to be sensitive to the horizontal component of specific force. The saccule organs, approximately perpendicular to the utricles, sense vertical shear forces and are roughly one-half as sensitive.

3. <u>Vestibular Modelling Research</u>

The need for development of a model of the human vestibular system can be illustrated best when one considers the advances made in modern aerospace technology. The high G environment of combat aircraft and space launch vehicles, the prolonged weightlessness of spacecrafts, and the motion experienced in large ships and tall buildings are products of twentieth century technology requiring the understanding of man's capacity to function in these environments.

The "state of the art" of current modelling capabilities is best illustrated in a PhD thesis by Ormsby [Ref. 11]. At the MIT Man-Vehicle Laboratory, under a NASA grant, Dr. Ormsby developed a mathematical model based on the known physiology of the human vestibular apparatus. The signal in noise model is capable of predicting near threshold and

supra-threshold perceived motion and attitude in the presence of random noise and spontaneous firing of the afferent sensors. It was then refined to be consistent with current neurophysical and psychophysical data. Included is a model of the central processor (the brain) and its interpretation of afferent dynamics with an à priori knowledge of the motion stimulus. Since it was difficult to obtain data resulting only from vestibular cues, the model is said to also reflect responses resulting from tactile and kinesthetic motion cues.

Separate models of the semicircular canals and the otolith organs are combined to yield the following estimates in the coordinate system of the head:

- perceived linear acceleration
- perceived rotational velocity
- perceived attitude (a unit vector in the perceived "down" direction).

The model has been successful in predicting illusions such as the dynamic elevator illusion in the absence of visual inputs. It also has produced results in close agreement with data describing perceived lateral tilt angle as a function of actual tilt angle in "1G" and "2G" environments. The pitch and roll sensations during a catapult launch were investigated and used to further refine the model.

It must be emphasized that the version of the model, as used in this thesis, is strictly a vestibular model without visual, tactile, or kinesthetic inputs. The integration of vestibular and visual cues is the subject of an ongoing

research program at the MIT Man-Vehicle Laboratory [Refs. 12 and 13].

4. Components of a Motion Base Control System

The human vestibular system is sensitive, not to motion, but to the higher derivatives of motion such as linear and angular acceleration. Thus only the "rate of change" of motion need be simulated. The simulation problem, then, is how to optimally simulate acceleration cues given fixed operating limits. (Hardware has inherent size, velocity, and inertial limitations, while computers have speed and accuracy limits.) A computer model of the aircraft produces acceleration vectors in response to control inputs and external factors such as wind and turbulence which are converted to simulator drive commands. Linear accelerations are simulated by tilting the cockpit cab (such as backward on application of thrust) at a rate below human rotational thresholds. Thus lateral and longitudinal acceleration cues can be simulated, but only the higher frequency vertical cues (such as turbulence and rapid pullups) can be simulated. After the cue has been transmitted, the cab is gradually returned to its neutral position. This tendency, known as "wash-out", keeps the cab near its center position to maximize its operating envelope for subsequent cues.

This section describes the main components of motion base control systems. The vast majority of motion base simulators have either "synergistic" platforms supported and

driven by linear hydraulic actuators or electro-mechanical drive systems with independent degrees of freedom. Digital computer programs for both system types are comprised of three main components:

- aircraft models which produce the particular flight dynamics and control feedback ("feel") characteristics
- "wash-out" filters which remove low frequency accelerations which tend to generate large amplitude movements
- "drive" programs which transform the aircraft motion to simulator motion commands.

This sequential process is shown in Figure 1. The motion of the aircraft about its six degrees of freedom is used to drive cockpit instrumentation, update navigational equipment, and drive external visual displays. The drive program consists of algorithms which compute:

- residual tilt which uses gravitational forces to simulate linear accelerations
- lead compensation for "quickening" the position commands to compensate for inertial lag in the machine's dynamics
- cab-to-drive mechanism transformations
- "soft" position, velocity, and acceleration limiting networks.

Although many additional safety features and utility functions are present in most programs, these are the primary

motion generating components. (See Refs. 14 and 15 for more in-depth, theoretical descriptions of control systems.)

5. Simulator Fidelity

Studies which evaluate motion control systems employ sophisticated means of calculating performance measures and compiling subjective pilot responses. Numerous studies have evaluated the handling quality differences between fixed and motion base simulators in an effort to understand the need for and the contribution of motion cues to the pilot. (See Refs. 15 and 16 for examples.) Improving stability characteristics for new aircraft or simulators often involves the analysis of pilot performance while system parameters are systematically changed. Verbal responses are analyzed to discern which aspects of the motion cues are deficient. Design of an aircraft control system typically entails a series of compromises and tradeoffs yielding handling qualities seldom optimum for any specific operating regime. Therefore, optimum performance does not reflect the fidelity of a motion system. Approximate duplication of such fundemental maneuvers as coordinated turn entries has been accomplished by matching aircraft and simulator accelerations about all six degrees of freedom. Since a precise duplication is unattainable due to the simulator's physical constraints, only the human operator can properly evaluate the differences.

Optimization of the control system for a new simulator is typically accomplished through numerous flights by

an experienced test pilot while engineers vary stability parameters. Many unpublished fidelity programs involve hundreds of manhours and expensive computer time in search of optimal control parameters. Often pilots need refresher flights in the aircraft to regain familiarity with its stability characteristics. One such study [Ref. 22] estimated that "eight hours of simulator time is sufficient to destroy a pilot's familiarity with the airplane to the point that he can no longer make valid qualitative judgements on flying qualities during closed loop tests."

C. PRESENT PURPOSE

Present D.O.D. emphasis is on new, higher fidelity flight simulators. A second avenue of approach is the improvement of present training devices having less than optimal flying qualities. Lack of fidelity has reduced the purpose of many devices to mere procedural trainers, while the motion and visual systems go unused. With new technology visual display systems, the shortcomings of the handling qualities and performance characteristics are magnified. As simulators assume a greater role in flight training and proficiency programs teaching advanced flying skills, the need for realistic duplication of the aircraft is apparent.

The Naval Air Test Center (NATC) has been conducting a fidelity improvement program for the Navy's inventory of Operational Flight Trainers and Weapon System Trainers [Ref. 22]. A team of fleet experienced pilots, flight test engineers, simulator and computer experts have been

successful in identifying performance, stability, and control parameters contributing to poor fidelity in all the subsystems. Although some hardware changes have been made, the majority of fidelity improvements have been accomplished by software reprogramming.

> "Aircraft manufacturers generally rely on wind tunnel data as a data base. Flight test data are not available because the first training device is usually delivered to the Fleet at about the same time that the first airplane comes off the production line. Since wind tunnel data represent at best only an estimate of airplane flight characteristics, the use of these data as a data base for a simulator results in poor flying qualities simulation. In addition, there has been no organized effort within the Navy or by any manufacturer to reprogram a simulator once flight test data are available."

> "Recent advances in the practical applications of control and estimation theory have made it possible to extract stability derivatives and other parameters from flight test data to a degree and with accuracy not possible in the past."

The degree of realism required in equipment, visual displays, and motion systems is a function of the level of training being performed and the amount of learning transfer desired. For a specific training device, whatever cost-effective measures (up to the point of diminishing returns) increase its fidelity would be welcomed, thus improving the transfer of learning.

The goal of this thesis is the development of a technique which would allow the simulator programmer (such as those of NATC's fidelity improvement program) to optimize the architecture and choice of parameters for simulator software. Work on an ongoing research program by Dr. L. R. Young at the NASA Langley Research Center and the MIT Man-Vehicle

Laboratory on the integration of visual and motion cues provided many original ideas for this work. An experiment was performed at the NASA Ames Research Center in the Flight Simulation Laboratory on a six-degree-of-freedom research simulator. The experiment was designed to test the hypothesis that there was no difference between simulator motion cues presented to the pilots. Five pilots performed a total of 161 simulator "runs", providing subjective ratings of different degrees of fidelity.

Using Ormsby's model of human dynamic orientation, a computer program was written to simulate the pilot's subjective evaluation of fidelity in objective terms. Validation of the simulation was performed using the experimental results as a data base. Another aim of this report is to confirm Dr. Ormsby's model to whatever extent possible.

II. METHOD

A. EXPERIMENT

1. Design

The pilot-subjects were asked to provide responses to different levels of motion fidelity. Fifteen sets of "wash-out" filter parameters were selected in an effort to produce discernably different motion cues during a flight task. For each "flight", subjects were asked to rate the rotational and linear acceleration cues relative to a rating scale and to provide a combined fidelity score. Thus, the dependent variables for the experiment were the three subjective ratings of the motion cues. The independent variables in the analysis were the motion cues and parameter sets.

The experimental results were analyzed according to a three-way factorial analysis of variance. Two fixed factors were motion (three levels) and parameter sets (15 levels). The third was subjects, a random factor (five levels). A conceptual model of the experimental design is shown in Figure 2.

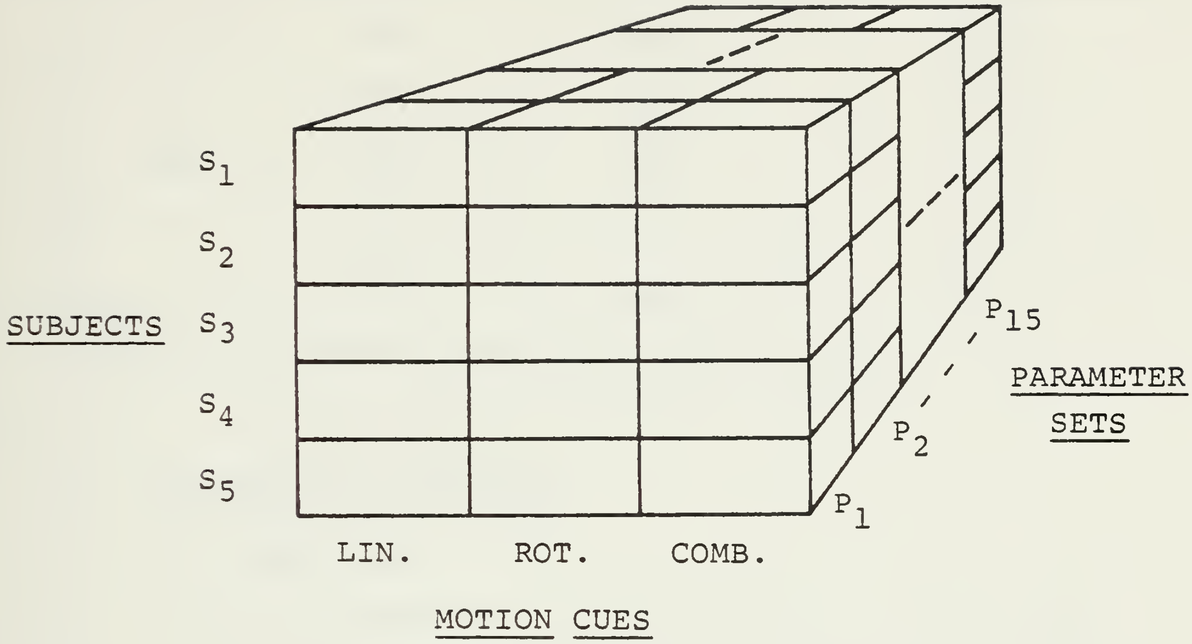


Figure 2: Model of Experimental Design

2. Subjects

Since the simulator was programmed as an F-15 (a combat fighter aircraft), subjects for the study were chosen for their experience as pilots in high performance aircraft. Although the subjects obtained for the experiment were experienced in military combat aircraft, only one was relatively current. The other four subjects were military trained airline pilots or flight engineers. Their pilot time experience is shown in Table I. Each was a volunteer and was compensated for his participation.

SUBJECT	HELO	SINGLE-ENGINE	MULTI-ENGINE	HIGH PERFORMANCE JET
1	-	550	2400	3050
2	-	180	860	130
3	600	160	350	250
4	-	30	-	800
5	-	1600	7500	2150

Table I: Subject Experience (pilot hours)

3. Stimuli and Apparatus

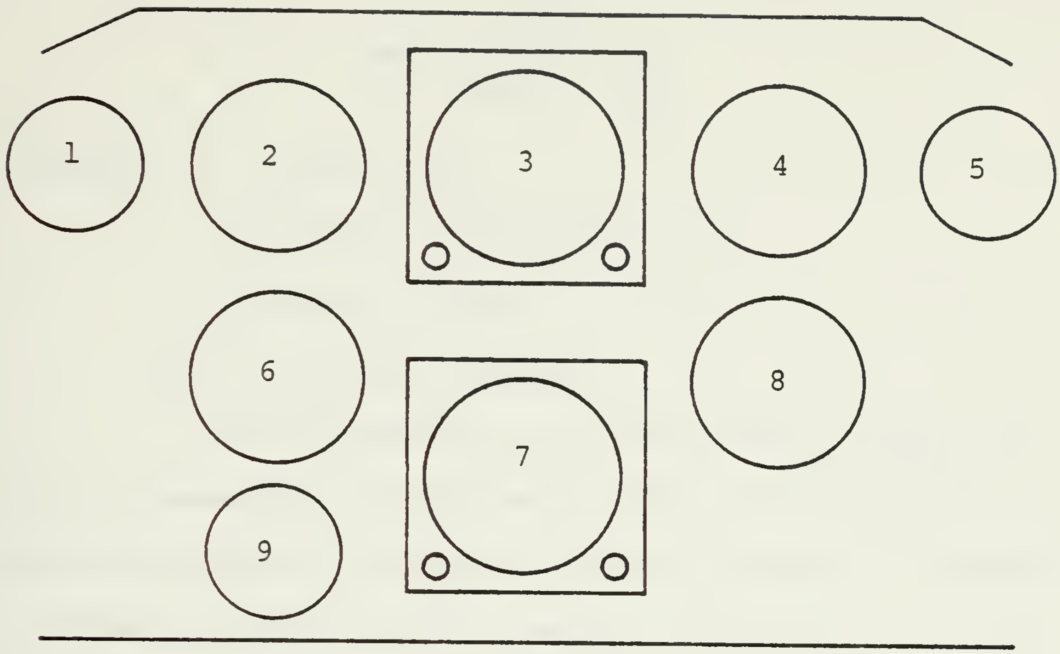
a. Simulator

The experiment was performed at the NASA Ames Research Center, in the Flight Simulation Laboratory. The simulator used in the experiment was the S.01 All-Axis Motion Generator, manufactured by the Northrop Corporation. The six-degree-of-freedom research simulator has independent drive mechanisms with a single-seat cockpit in the center of its operating envelope. The machine's linear position limits are ±9 feet; the rotational limits are ±45 degrees from its neutral position. The simulator was controlled by an EAI 8400 computer. The computer programming included "soft" position, velocity, and acceleration limiting networks which prevent the simulator from reaching the "hard" mechanical limits. A more in-depth study of the machine's operating characteristics and mathematical development of its "drive logic" is contained in Reference 15.

As with most simulators, the cockpit was enclosed preventing visual reference to outside of the cab.

The cockpit configuration was that of a typical single-seat aircraft, controlled by a stick, rudder pedals, and power lever. Since visual cues from external displays and artificial attitude instrumentation tend to interact with vestibular cues in a way not fully understood, use of these displays was minimized. (The simulator was equipped with a terrain modelboard visual system, but the projection equipment was off for the duration of the experiment.) The main instrument panel was organized in a conventional "T" arrangement as shown in Figure 3. Although the basic instrument array included an artificial horizon (attitude gyro), it was felt that its absence would impose an unusually high workload level on the subject and tend to lengthen the learning process inherent in the task. Also, the more familiar the cockpit environment was to the subject, the quicker would be his adaptation to the task, allowing maximum attention to the motion cues.

An intercom system, with a "hot" microphone for the pilot, allowed two-way communication between the subject, system operators, and experimenter. Verbal responses by the pilots were recorded on a cassette tape recorder. The experimenter monitored the progress of the task on a strip chart recorder, displaying altitude, airspeed, vertical speed, and heading.



1 - Clock with Sweephand

2 - Airspeed Indicator

3 - Attitude Gyro

4 - Altimeter

5 - RPM Gauge

6 - Angle of Attack Indicator

7 - Horizontal Situation Indicator

8 - Vertical Speed Indicator

9 - Turn Needle and Ball

Figure 3: Main Instrument Panel

The "wash-out" filter, which interfaces the mathematical aircraft model with the "drive" program, is composed of six separate digital filters, one for each degree of freedom or "channel". Each second order, high pass filter is described by a linear gain, a natural frequency, and a damping ratio with a Laplace transform equation of the form:

$$\frac{Ks^2}{s^2 + 2\zeta w_n s + w_n^2}$$

where: K = linear gain

s = Laplace complex variable

ζ = damping ratio

w_n = natural frequency

Through consultation with NASA personnel, 15 sets of parameters (18 parameters each) were chosen to produce noticeably different levels of realism. Values of the filter parameters are presented in Appendix B. The fidelity associated with each set could not be predetermined, except that the range over which each parameter varied was thought to be sufficient to produce noticeable differences in motion cues.

b. Task

Initially, the experiment was designed to analyze two different tasks in order to examine any significant difference in subject responses. Due to time constraints and equipment malfunctions, the second task, an ILS (instrument landing system) approach to a waveoff, was eliminated from the study.

Design of the task reflected many considerations. It was recognized that the task should be:

- similar to those used in RDT&E and training programs so that the maximum extrapolation of results could be made
- relatively familiar to the subjects and well within

their capabilities to lessen the time spent mastering it

- well within the capability of the simulator to minimize machine error and breakdowns
- long enough to expose the subject to a full variety of motion cues and allow him ample time to subjectively evaluate them.

A three and one-half minute "basic airwork" task was chosen to simulate the low frequency flight maneuvers common to the terminal phase of flight operations (climb-out after takeoff, descent prior to approach and landing, etc.). Subjects were provided enough information to rapidly learn the task and to execute it consistently from trial to trial. As shown in Figure 4, two versions of the flight pattern were devised. The direction of the initial turn was randomized. During the second replication of each parameter set, the turn was made in the opposite direction.

c. Rating Scales

Subjects were asked to subjectively judge the fidelity of the motion cues encountered during the task using two rating scales. The pilots scored separately the linear (or translational) and the rotational motion cues on a graphic eight-point scale. The cues were also rated in comparison to a "standard" motion (presented using the established set of wash-out parameters employed on the simulator). Thus, the subjects rated the motion fidelity on both an absolute and comparative basis.

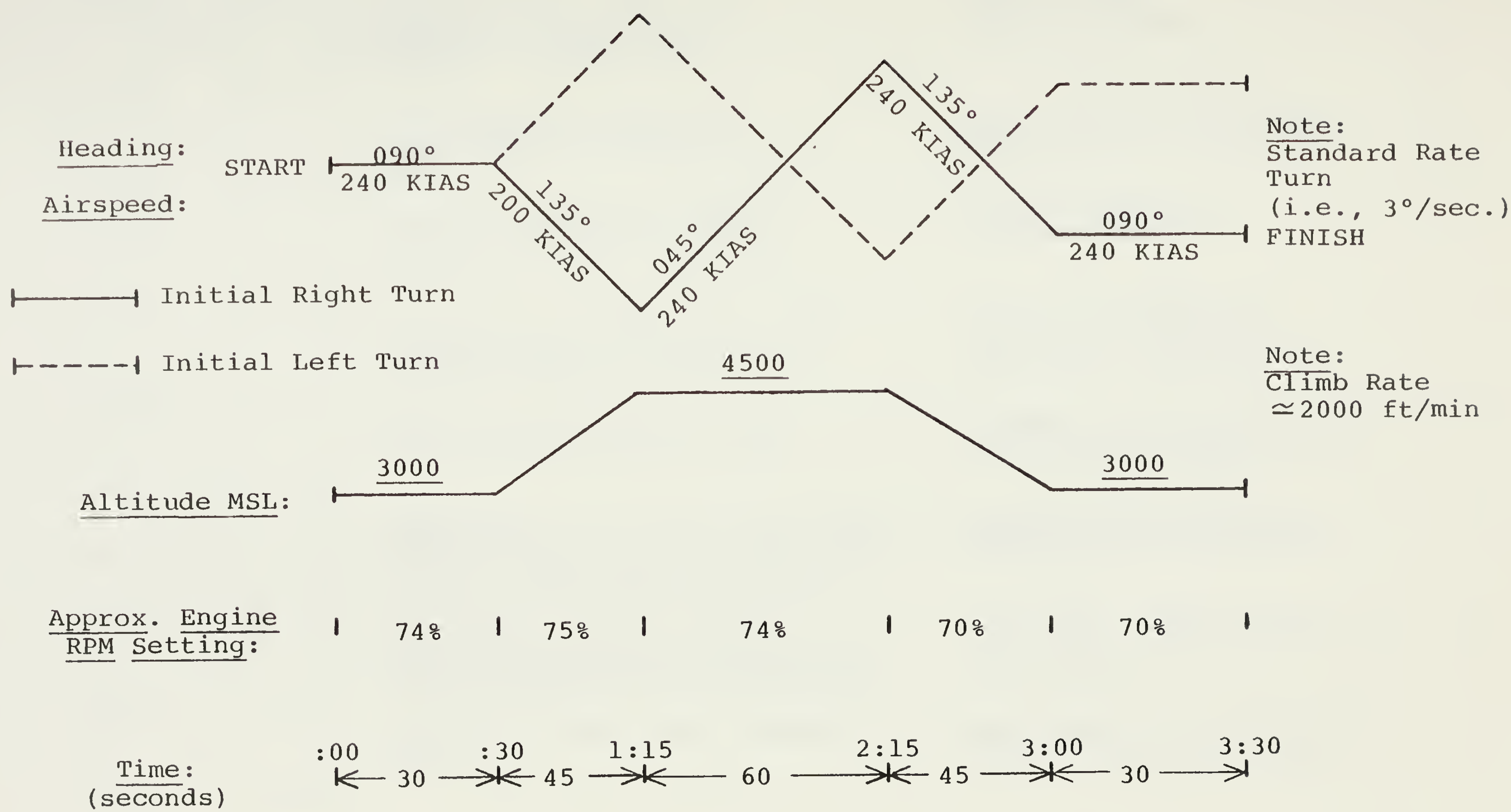


Figure 4: Flight Task Pattern

COMPONENT RATING SCALE

LINEAR		ROTATIONAL	RESPONSE TO CONTROL INPUTS	MOTION DEFICIENCIES
	8		Excellent "feel", smooth, very responsive, requires normal attention to the task, highly realistic	None discernible, extremely realistic
	7		Very good "feel", responsive, normal attention required, ILS tracking with ease, no improvement needed	Few, slight or insignificant, just noticeable, no improvement required
	6		Good "feel", responsive, moderate attention level required, tracking with moderate effort, improvement desired	Few minor deficiencies, improvement desired
	5		Fair, quick or sluggish response, full attention required, ILS tracking with considerable effort, required control motion too small or too large	Many minor, objectionable deficiencies, improvement needed, moderately realistic
	4		Poor, major improvements required ILS tracking only with great effort	Numerous, minor/many major deficiencies, very objectionable, much improvement needed
	3		Unsatisfactory, very slow or overly quick response, "heavy" or "light" feel, difficult to control, ILS tracking nearly impossible, inordinate level of attention required	Numerous, major deficiencies, many unpleasant characteristics, unrealistic
	2		Unacceptable, extremely sluggish or quick to respond, often unstable, extremely high level of attention and compensation required to maneuver, tracking impossible	Unacceptable, numerous gross deficiencies, nearly uncontrollable, very unrealistic
	1		Unresponsive, uncontrollable, unstable, erratic	Uncontrollable, lacks any sense of realism, erratic, unpredictable

Figure 5: Component Rating Scale

<u>COMPARATIVE RATING SCALE</u>

Rate the motion characteristics in comparison to the "Standard Motion"

+3		Much more desirable, highly superior preferred to the "standard" by far
+2		Better preferred to the "standard"
+1		Just noticeably better preferred only slightly to the "standard"
-1		Just noticeably inferior "standard" is slightly preferred
-2		Worse "standard" is preferred
-3		Much worse, highly inferior "standard" is preferred by far

Figure 6: Comparative Rating Scale

4. Procedure

After the subjects read the instructions (see Appendix A), further questions were answered. The intent and goals of the experiment were discussed freely with the subjects. They were allowed to become familiar with the simulator cab during one practice run before the trial runs began. Each was given a pilot kneeboard containing a diagram of the task, the two rating scales, and a list of topics from which relevent comments were volunteered following each run.

The sequence of wash-out parameter sets presented to the subjects was randomized; a different sequence was presented to each subject. The "standard" motion was presented once at the beginning of each session (twice at the start of a subject's first session) and every fourth run thereafter. A typical session of 12 simulator runs is shown in Figure 7.

$P_0 \quad P_2 \quad P_8 \quad P_{15} \quad P_0 \quad P_{11} \quad P_{14} \quad P_6 \quad P_0 \quad P_1 \quad P_5 \quad P_{13}$

where: P_0 = "standard" parameter set

Figure 7: Typical Sequence of Parameter Sets

No reference was made to the parameter set number or their values during the trial runs.

At the end of each task, subjects rated the motion cues and provided subjective comments relevent to the specific run via the intercom. The parameter set was changed

and the simulator was reinitialized for the next run. After each session, subjects were allowed to review their responses and discuss the session (comments were not recorded).

Factors which were uncontrollable were the number of sessions and runs per subject. Due to equipment malfunctions and scheduling constraints the sessions and runs varied widely as shown in Table II.

SUBJECT	NO. SESSIONS	NO. RUNS*
1	3	24
2	3	37
3	4	42
4	2	26
5	2	31

*Includes "Standard Motion" Runs

Table II: Sessions and Runs by Subjects

B. SIMULATION

1. Model Assumptions

The subjective process by which a pilot compares the motion of a simulator with that of an aircraft is, obviously, a complex psychological one. If a model of this human comparative method were constructed, it could predict a pilot's response to the fidelity of a simulator's motion characteristics. The structure of the computer simulation described in this section is based on the assumption (as proposed by

Young, Ref. 13) that the pilot's evaluation is a function of the difference between:

- the simulator motion cues as perceived by the pilot and
- the perceived motion of the aircraft as experienced by the pilot.

Assuming that Ormsby's vestibular model of human dynamic orientation provides a reliable estimate of motion perception, it was then a matter of deriving motion histories of the aircraft and the simulator performing "identical" maneuvers.

2. Design

During the experiment described in Section A, the output of the computerized aircraft model (see Fig. 1) was recorded on magnetic tape during each run. The data consisted of accelerations for each degree of freedom recorded during each cycle of the discrete programming. The cycle time used in the experiment was 50 milliseconds, chosen so as to be compatible with the input sampling rate of the dynamic orientation program. (Sufficient data was also recorded to document the specific pilot and run number.)

The flight acceleration data was used as an input to the S.01 simulator's drive program, a copy of which is used in this simulation. The simulation is a deterministic model with no random variables. Figure 8 is a block diagram of the simulation. Since the dynamic response of the motion platform contributes to the motion cues presented to the pilot, but is

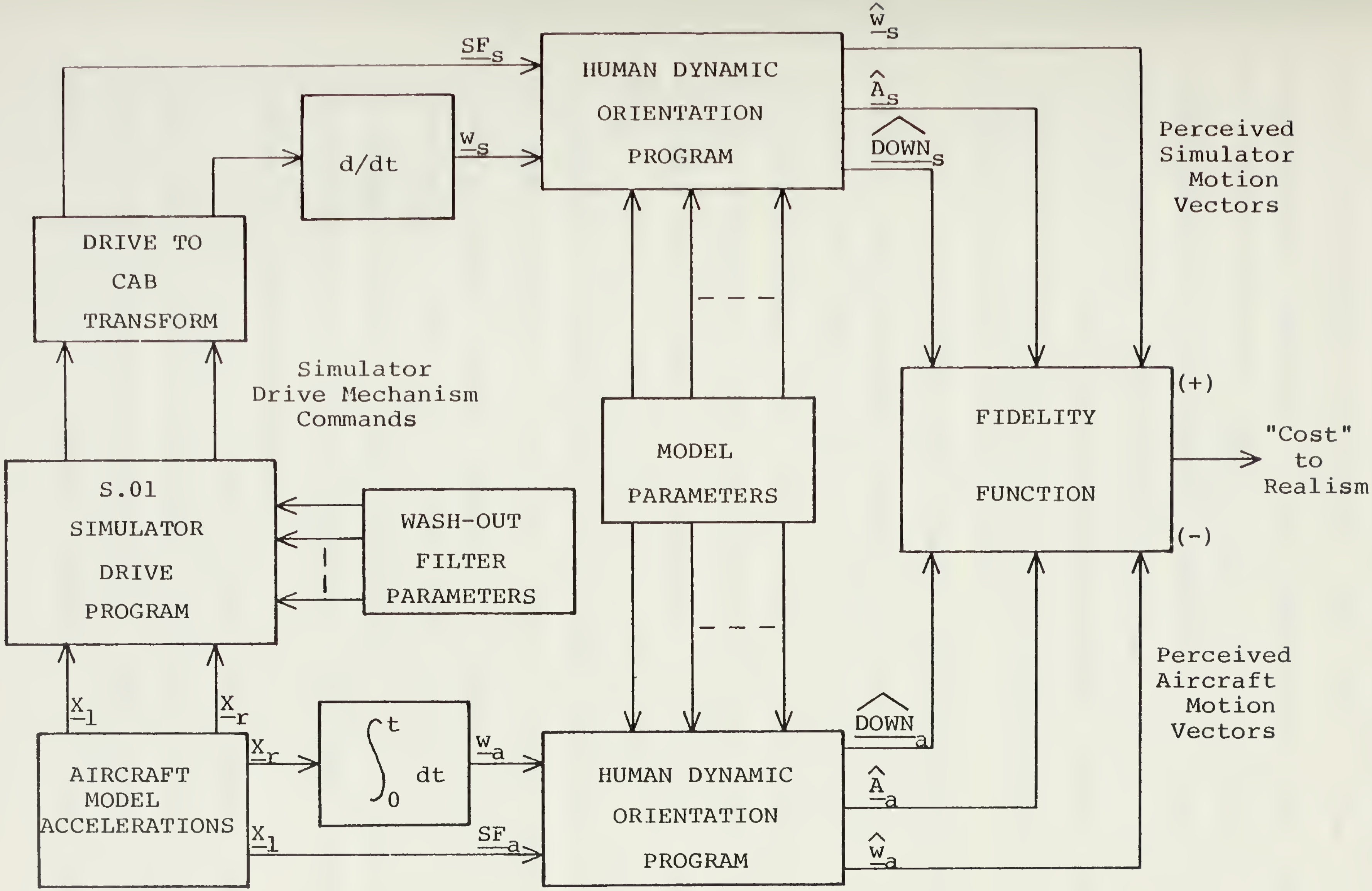


Figure 8: Simulation Block Diagram

not a factor in this simulation, the lead compensation network in the program is bypassed. The result is the closest approximation available to the actual motion of the cab. The outputs from this program are linear acceleration commands and rotational position commands of the platform's drive mechanism. A transformation then converts these signals back to vectors describing the cockpit motion. The rotational position commands are then differentiated to produce rotational velocity vectors.

Inputs to the human dynamic orientation program are discrete time histories of specific force vectors (in units of "G's") and angular velocity vectors (radians/sec.) in the coordinate system of the pilot's head. It is sampled at discrete intervals of 100 milliseconds; thus the simulator and aircraft motion vectors are sampled at every other time frame. Although this represents a loss of input information, considerable recomputation of many model parameters would have been necessary to alter the input or output rates. The output of Ormsby's model consists of vectors in the coordinate system of the subject describing his perception of rotational velocity, linear acceleration, and attitude (perceived vertical or "down" direction). The model's output rate is one sample per second.

Motion vectors of the aircraft are computed from the flight data after the rotational velocity is formed by integrating the rotational acceleration. These vectors are then used as inputs to the dynamic orientation program to produce

perceived aircraft motion. Notation used in the block diagram is defined as follows:

$\underline{X}_l$, $\underline{X}_r$ = aircraft model linear and rotational acceleration vectors, respectively

$\underline{SF}_a$, $\underline{SF}_s$ = specific force vectors for the aircraft and simulator, respectively

$\underline{w}_a$, $\underline{w}_s$ = rotational velocity vectors for the aircraft and simulator, respectively

$\hat{\underline{A}}_a$, $\hat{\underline{A}}_s$ = perceived linear acceleration vectors for the aircraft and simulator, respectively

$\hat{\underline{w}}_a$, $\hat{\underline{w}}_s$ = perceived rotational velocity vectors for the aircraft and simulator, respectively

$\widehat{\underline{DOWN}}_a$, $\widehat{\underline{DOWN}}_s$ = perceived attitude vectors for the aircraft and simulator, respectively.

III. RESULTS

A. EXPERIMENTAL RESULTS

1. Subjective Responses

Verbal responses recorded at the end of each task allowed the experimenter to understand such considerations as the learning curve, workload, etc., associated with the task. The act of commenting on each run gave subjects the opportunity to critically review the flight and to adjust their scores as opinions were formulated. This section is a brief summary of pilot comments pertaining to the experimental flights.

Differentiation between the rotational and translational motion cues was discussed with the subjects as the experiment progressed in hopes that more reliable responses would result. Following his fifth run, one subject attempted to further define his task:

> "I'm to separate pitch and roll from sideways, horizontal, or longitudinal axis motion as linear, whether it be throttle acceleration or just sideways gusts."

Several pilots commented that they were more confident of their responses during second and subsequent sessions as they familiarized themselves with the task and learned more about the characteristics of the motion to be rated. One pilot mentioned that it was difficult to discern whether motion cues were more realistic or his ability to control the simulator had improved. During a subject's

second session he commented:

> "....the oscillations I was in the other day; at first I thought I was experiencing pitch oscillations. What they are is the linear, up and down, that I was feeling before; so I'm getting used to the motion.... at least understanding it better."

All the pilots noted that the workload level varied significantly from run to run as the motion cues changed. Abnormal cues often caused subjects to react improperly; a response which presumably would not have occurred in a fixed-base simulator. One subject noted the difference between the motion and cockpit instrument indications:

> "I was getting a definite rotational pitch sensation and frequently corrected with [forward] stick.... which I didn't want to do."

All subjects noted vibrations induced by the motion base mechanism. Normally turbulence masks these anomalies to some extent. Since it was not used in the experiment, the mechanical limitations tended to put a ceiling on the subjective motion ratings. One subject was allowed a practice run with a minimal level of turbulence at the beginning of his second session. He commented:

> "...turbulence...simply detracts from the ability to differentiate...how the controls are functioning. I think I'm less able to determine how much of it is ...turbulence or control response with the turbulence."

2. <u>Correlation of Ratings</u>

Scores from the three rating scales represent discrete data possessing ordinal properties. It can be argued that each rating scale attempts to define levels separated by equal intervals; it is not immediately evident that each subject

perceived the scales in this manner. Thus, it cannot be assumed that the data comes from an interval scale, an assumption for use of parametric statistics. As a measure of the reliability of the data, nonparametric correlations were calculated. Scores from the standard motion were excluded from this and subsequent analysis since subjects were told which runs were the standard and instructed to use it as a comparative reference for the other 15 parameter sets. An average score was formed for each subject/motion/parameter set combination analogous to each "cell" of the experimental design (see Fig. 2). Spearman rank correlation coefficients between subjects were computed for the linear, rotational, and combined ratings separately. The correlations with respective significance levels are shown in Table III.

		SUBJECTS				
		1	2	3	4	5
SUBJECTS	1	1.0	.5240*	.0731	.6810***	.1264
	2		1.0	.1435	.5668**	.1722
	3			1.0	.2263	.5666**
	4				1.0	.0250
	5					1.0

Significance Levels: *$p<.05$, **$p<.01$, ***$p<.005$

Table III(a); Correlation Between Subjects for Linear Motion Ratings

		SUBJECTS				
		1	2	3	4	5
SUBJECTS	1	1.0	.4857*	.1244	.6081**	.4367
	2		1.0	.2823	.5957**	.4157
	3			1.0	-.0703	.3963
	4				1.0	.2485
	5					1.0

Table III(b): Correlation Between Subjects for Rotational Motion Ratings

		SUBJECTS				
		1	2	3	4	5
SUBJECTS	1	1.0	.5449*	.5065*	.7907***	.2456
	2		1.0	.5321*	.6147**	.4700*
	3			1.0	.4481*	.4968*
	4				1.0	.2564
	5					1.0

Significance Levels: *p<.05, **p<.01, ***p<.005

Table III(c): Correlation Between Subjects for Combined Motion Ratings

Overall agreement between the five subjects was computed using the Kendall coefficient of concordance as shown in Table IV.

RATINGS		
Linear	Rotational	Combined
.4483*	.4835*	.5914*

Significance Level: *$p<.005$

Table IV: Coefficient of Concordance Among Subjects for Motion Ratings

The ability of subjects to repeat ratings given the same stimuli was investigated. Due to time constraints only 41 subject/parameter set combinations were replicated. Correlations between the first and second observations for these combinations is shown in Table V.

RATINGS		
Linear	Rotational	Combined
.4882*	.4234*	.5559**

Significance Levels: *$p<.005$, **$p<.0005$

Table V: Spearman Rank Correlation Between Replications

3. Analysis of Variance

Analysis of Variance techniques were used to determine if different motion cues significantly affected the ratings and if interactions existed which would help explain the weak between-subject correlations obtained. Although

the discrete rating scale data violates the assumptions of interval data and normality of the error distribution, an approximate ANOVA was computed. Since the rating scale consists of essentially 15 levels separated by intervals designed to be equal, the assumption of interval data is not entirely untenable. Madill [Ref. 17] reports that the distribution of the error term in the regression model for discrete rating scale data is often binomial in nature. Thus, the variance is not independent of the mean as required for ANOVA analysis. The transformation which attempts to equalize the error variance for the binomial distribution is the $\arcsin\sqrt{X}$ transformation. A transformation of the form:

$$R' = 7\arcsin\sqrt{\frac{R-1}{7}} - 1.0 \qquad (1)$$

where: R = raw rating scale score

R' = transformed score

was used. The effect is minimal in the range 3.0 to 6.0 and tends to expand the ends of the scale. The ANOVA table is shown in Table VI. Due to the large percentage of missing data, the three-way interaction sum of squares is included in the error sum of squares with its degrees of freedom.

SOURCE	d.f.	S.S.	M.S.	F RATIO
Subjects (S)	4	83.91	20.98	44.24*
Motion Cues (M)	2	1.08	.54	.33
Parameter Sets (P)	14	119.99	8.57	4.86*
S x M	8	13.13	1.64	3.46*
S x P	56	98.71	1.76	3.72*
M x P	28	13.25	.47	.99
Error	235	111.91	.48	
Total	347	441.98		

Significance level: $*p<.001$

Table VI: ANOVA Table for the Experiment

A nonparametric analysis of variance was performed to support the results of the approximate ANOVA above. The subject/parameter set averages were tested using the Friedman two-way analysis of variance by ranks [Ref. 18]. The three motion cues were investigated separately. Results showed that both the linear and rotational motion ratings were significantly different at the .01 level. The combined ratings were different at the .001 significance level.

A Duncan multiple range test with unequal replications [Refs. 19 and 20] was performed on the means of the parameter sets. Results using the .05 level of significance are shown in Figure 9. Any two means underscored by the same line are not significantly different.

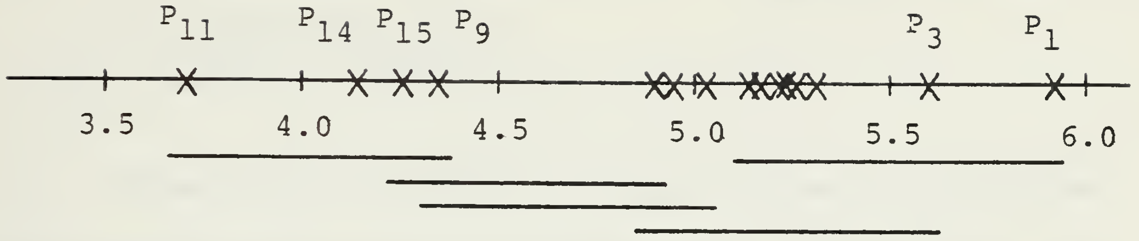


Figure 9: Parameter Set Averages

B. SIMULATION RESULTS

1. Fidelity Models

The available signals at the simulation output consist of vectors estimating the pilot's perceived motion and attitude. Each human dynamic orientation program (see Fig. 8) computes perceived linear acceleration, angular velocity, and attitude vectors. Algorithms for comparing these time varying signals were constructed based on the assumption that the greater the difference between corresponding vectors for the aircraft and simulator, the less the fidelity. The following vector variables are available as inputs to the fidelity function. (Notation is consistent with that used by Young in Ref. 12.)

$\hat{\underline{A}}_a(t)$ = perceived aircraft linear acceleration

$\hat{\underline{A}}_s(t)$ = perceived simulator linear acceleration

$\hat{\underline{w}}_a(t)$ = perceived aircraft angular velocity

$\hat{\underline{w}}_s(t)$ = perceived simulator angular velocity

$\widehat{\underline{DOWN}}_a(t)$ = perceived aircraft attitude

$\widehat{\underline{DOWN}}_s(t)$ = perceived simulator attitude

where: a = aircraft, s = simulator, $\wedge$ indicates a perceived quantity

(t) indicates a time varying function

Three different fidelity functions were constructed to be compared with the experimental data. The first is an average percent error model as suggested by Young:

> "When the [motion] sensations are clearly supra-threshold, the most likely candidate is just percent error, the ratio of perceptual error to the correct quantity. When the model indications for 'correct' perceptions are subthreshold, it seems more logical to assess a large penalty for errors that are large compared to the threshold value."

For each sample output (one per second) the following "cost to realism" indices were computed.

$$\frac{|\Delta \hat{\underline{A}}(t)|}{\max\left\{|\hat{\underline{A}}_a(t)|,\ \hat{A}_{thr}\right\}} = C_A(t) \qquad (2a)$$

$$\frac{|\Delta \hat{\underline{w}}(t)|}{\max\left\{|\hat{\underline{w}}_a(t)|,\ \hat{w}_{thr}\right\}} = C_w(t) \qquad (2b)$$

$$|\Delta \widehat{\underline{DOWN}}(t)| = C_D(t) \qquad (2c)$$

where: Δ = the difference between aircraft and simulator vectors

$|\underline{x}|$ = amplitude of vector x

thr = threshold value

Threshold values used in the simulation were those computed in Ormsby's vestibular modelling thesis [Ref. 11]:

$$\hat{A}_{thr} = .005 \text{ "G's"}$$

$$\hat{w}_{thr} = .0146 \text{ radians/sec}$$

The vector $\underline{\widehat{DOWN}}$ is a constant amplitude unit vector; thus, the cost index is simply the magnitude of the difference vector. Averages for each of the three cost indices were computed over each simulator run. Though the task was designed to last three and one-half minutes, subjects often used over four minutes to complete it. Aircraft acceleration data from each run, up to four minutes, was used as input to the simulation. The following average cost values were computed:

$$\bar{C}_A = \frac{1}{n} \sum_{i=1}^{n} C_A(t_i) \tag{3a}$$

$$\bar{C}_W = \frac{1}{n} \sum_{i=1}^{n} C_W(t_i) \tag{3b}$$

$$\bar{C}_D = \frac{1}{n} \sum_{i=1}^{n} C_D(t_i) \tag{3c}$$

where: n = number of output time frames

Several subjects noted that during many runs there existed unexplained and unrealistic motion excursions about the rotational axis, but more pronounced in the translational cues. A measure using the same cost indices which is more sensitive to these rapid anomalies (if caused by the programming and not the hardware) is a root mean square (RMS) figure. The second fidelity function computes RMS cost values as follows:

$$\tilde{C}_A = \sqrt{\frac{1}{n}\sum_{i=1}^{n} C_A^2(t_i)} \tag{4a}$$

$$\tilde{C}_W = \sqrt{\frac{1}{n}\sum_{i=1}^{n} C_W^2(t_i)} \tag{4b}$$

$$\tilde{C}_D = \sqrt{\frac{1}{n}\sum_{i=1}^{n} C_D^2(t_i)} \tag{4c}$$

It is not unreasonable to assume that pilot responses may simply be proportional to the amplitude of the error vector. The third fidelity function computes the average of each error vector; the numerators of equations 3a, 3b, and 3c.

$$\bar{A} = \frac{1}{n}\sum_{i=1}^{n} |\Delta \underline{\hat{A}}(t_i)| \tag{5a}$$

$$\bar{W} = \frac{1}{n}\sum_{i=1}^{n} |\Delta \underline{\hat{W}}(t_i)| \tag{5b}$$

$$\bar{D} = \frac{1}{n}\sum_{i=1}^{n} |\Delta \underline{\widehat{DOWN}}(t_i)| \tag{5c}$$

A total of 133 simulator runs were recorded successfully; 97 of which used wash-out parameter sets other than the standard set. Minimum, maximum, and average cost indices computed by the three fidelity functions are shown in Table VII.

	MINIMUM	AVERAGE	MAXIMUM
$\bar{C}_A$	.9959	1.0788	1.4830
$\bar{C}_W$	.5776	.7603	.9457
$\bar{C}_D$	.0626	.0898	.1243
C_A	.9983	1.1428	2.0106
C_W	.6750	.8309	1.0671
C_D	.0715	.1045	.1451
$\bar{A}$	.0403	.0612	.0911
$\bar{W}$	.0108	.0179	.0282
$\bar{D}$	.0626	.0898	.1243

Table VII: Cost Index Values Computed by the Simulation

2. Experimental Optimization

Response of the simulation to changes in the wash-out parameters was investigated to determine its adaptability to experimental optimization methods such as an optimal gradient search. If the simulation is to be an effective research tool for determining optimal control system variables, then its response characteristics must be of a tractable form. Time did not allow for a full exploration of its response

"surface" by an optimization routine, nor were manual methods employed to search for a minimum "cost" solution.

Linear and rotational wash-out filter gains were varied over the range of the parameters used in the experiment. The response function was arbitrarily chosen to be:

$$f(\tilde{C}_A,\tilde{C}_w,\tilde{C}_D) = \tilde{C}_A + \tilde{C}_w + \tilde{C}_D \qquad (6)$$

The linear gains, K_l, were fixed at different levels while the rotational gains, K_r, were varied together from 0.0 to 0.8 at intervals of .05. The response curves obtained are shown in Fig. 10. The basic parameter set used during these simulation runs was P_9.

C. SIMULATION VALIDATION

Validation of the simulation consisted of comparing the subjective fidelity ratings with predictions from the simulation. It was then a question of which ratings and cost indices to analyze. Since the strongest correlations between subjects were for ratings of the combined motion cues, the combined ratings were compared to the following unweighted linear combinations of the cost indices:

$$\bar{C}_A + \bar{C}_w + \bar{C}_D \qquad (7a)$$

$$\tilde{C}_A + \tilde{C}_w + \tilde{C}_D \qquad (7b)$$

$$\bar{A} + \bar{W} + \bar{D} \qquad (7c)$$

Spearman rank correlation coefficients were computed for each subject and cost index combination. (Fidelity ratings

Figure 10: Simulation Response to Varying Filter Gains

were subtracted from a constant to yield scores proportional to the cost to fidelity.) The results are shown in Table VIII.

SUBJECTS	$\bar{C}_A + \bar{C}_W + \bar{C}_D$	$\tilde{C}_A + \tilde{C}_W + \tilde{C}_D$	$\bar{A} + \bar{W} + \bar{D}$	NO. RUNS
S_1	.4147*	.5138**	.2673	14
S_2	.2893	.3445*	-.0403	21
S_3	.3802**	.3986***	-.1489	26
S_4	.0542	.2965	-.0599	13
S_5	.3217*	.3227*	.3953**	23

Significance levels: *$p<0.1$, **$p<.05$, ***$p<.025$

Table VIII: Spearman Rank Correlations Between Subjects and Simulation Cost Indices

Weighted sums of the cost indices were computed by multiple linear regression techniques in order to improve the correlations. Using the assumptions for parametric methods given for the analysis of variance above, a regression model of the form:

$$R'_C = a_1\tilde{C}_W + a_2\tilde{C}_A + a_3\tilde{C}_D + a_4 \qquad (8)$$

where: $R'_C = 8 - R_C$

R_C = combined motion rating

a = regression coefficients

was used to compute regression coefficients for each subject and for all subjects combined. Results are shown in Table IX.

	Regression Coefficients a_1	a_2	a_3	a_4	MULT. R	Sig.@ Level
SUBJECTS S_1	-.530	2.697*	5.676	-.874	.5660	.2571
S_2	2.819	1.845	-17.628*	.547	.4926	.1826
S_3	3.578	2.030	1.811	-2.926	.3671	.3541
S_4	-6.540	.449	-7.916	9.312	.2949	.8346
S_5	8.792*	.780	9.096	-4.999	.4589	.2030
All Subjects	-1.336	1.513**	-3.070	2.653	.2442	.1245

@ Significance level associated with the ANOVA F ratio for the regression sum of squares

Significance levels: *p<0.1, **p<0.05

Table IX: Regression Coefficients for Combined Ratings versus RMS Cost Indices

IV. DISCUSSION

Results of the experiment tend to reject the hypothesis that similar motion cues were presented to the subjects. As shown in Figure 9, a cluster of nine parameter sets exists toward the center of the range of means. Parameter sets one and three appear significantly better than the others, while sets 9, 11, 14, and 15 are significantly inferior to the others. The fact that the center group of parameter sets produced indistinguishable motion cues is a probable explanation for the weak correlations between subjects. Parametric Pearson product-moment correlations were computed yielding similar results at comparable significance levels. The highly significant coefficients of concordance also indicate that ordinal agreement between subjects was less than anticipated. The overall higher correlations for the combined motion ratings infer that subjects were capable of yielding more reliable scores after rating both linear and rotational motion cues on an absolute scale, followed by a pairwise comparison with the standard motion. The higher correlations could also be explained by the fact that several subjects said their responses resulted from an overall impression of the motion cues rather than a subjective average of the linear, rotational, and comparative scores. Two subjects rated the combined motion cues higher than either linear or rotational scores for several runs.

Comments by the pilots indicate that a large percentage of the variance of the pilot ratings is likely due to unrealistic dynamics of the motion drive mechanism. High frequency vibrations in the system were not as distracting and did not seem to lessen fidelity as much as the low frequency, larger amplitude anomalies experienced by the subjects. Whether these were caused by the software or hardware is not known.

Cost indices computed by the simulation show large differences between outputs of the vestibular models. Errors ranged from 58 to 148 percent of the perceived aircraft motion vectors as shown in Table VII. Whether this typifies the capabilities of the S.01 simulator or is largely a result of programming limitations and inaccuracies is not readily apparent. A significant amount of error is most likely due to roundoff, precision limits, and the discrete nature of the program. Motion histories of the aircraft and simulator have cycle times of .05 seconds, while the output rate of each vestibular model is one per second. This represents a considerable loss of information. If the output sampling rate equaled the input rate, it may have been more responsive to the rapid motion anomalies noted by the subjects. A quick excursion lasting less than a second may not have been reflected in the output of the human dynamic orientation model.

The aircraft model used during the experiment was that of the F-15 fighter. Ideally, subjects with recent F-15 experience should have been chosen, but due to time and availability

constraints selection of the pilots was less than optimal. It was felt that this factor contributed greatly to the lack of higher correlations of the ratings between subjects. This conclusion was supported by the weak correlations between the first and second replications of the parameter sets. This also implies an inability of the subjects to repeat the task as well as inconsistent responses between subjects.

Response of the simulation to changes in wash-out filter gains indicated a definite tendency for convexity in the neighborhood of minimum output. This can be explained intuitively. When the gains are relatively low, the lack of motion cues produces a large discrepancy between perceived aircraft and perceived simulator motions. When the gains are high, cues become overly rapid, exagerated, and frequently cause the simulator to reach its "soft" programming limits. When reached, the limits force the linear and rotational cues to become uncoordinated, reducing fidelity. The simulation output, defined by equation 6, varied over a small range as the rotational gains were varied as shown in Figure 10. For each level of the linear gains, the output varied only 2 to 4 percent. Parameter sets which produced significantly better motion cues, P_1 and P_3, were comprised of filter gains set at 0.3. The tendency for the simulation output to minimize at approximately 0.3 indicates a capacity to predict subjective preferences for motion cues produced by these parameter sets. The simulation was also run with

the linear gain, K_l, set at 0. Response was less than that for K_l set to 0.1 throughout the range of K_r. This implies that optimal motion cues include very little linear acceleration for the specific flight used as input to the simulation.

Comparison between the simulation output and subject responses is summarized as follows:

- Positive correlations were obtained for the first two fidelity models, equations 7a and 7b (see Table VIII).
- The third function, equation 7c, showed little correlation with the exception of subject five.
- The second fidelity function consistently produced higher and more significant correlations infering that the RMS cost indices are a better method for simulating subject responses.
- Linear regression using the RMS cost indices as independent variables and the combined motion cue ratings as dependent variables(equation 8) showed little consistency of regression coefficients among the five subjects (see Table IX).
- Linear regression analysis yielded multiple correlations not appreciably better than the correlations for the unweighted cost index combination.
- Very little correlation was found between ratings of the linear and rotational motion cues and the corresponding cost indices, such as the rotational ratings and $\tilde{C}_w$.

Nine of the 15 wash-out filter parameter sets were grouped in the center of the range of mean responses as shown in Figure 9. Since these did not represent significantly different means, Spearman rank correlations were computed between the subjects' combined scores and the second fidelity function, equation 7b, for the remaining six parameter sets. The results are shown in Table X.

	SUBJECTS				
	S_1	S_2	S_3	S_4	S_5
Correlation	.9710**	.0748	.6545*	.5000	.7660*
No. of Runs	6	7	10	3	8

Significance levels: $*p<.05$, $**p<.01$

Table X: Spearman Rank Correlations for the Remaining Six Parameter Sets

With the exception of subject two, the subjects showed a marked increase in correlation with the simulation results. Although the sample sizes for this post hoc analysis were small, three of the five correlations were significant. It was noted that the correlations compared closely, rankwise, to the flight experience each pilot had in high performance jet aircraft as indicated in Table I.

VI. RECOMMENDATIONS

Recommendations for further research include suggestions for improvement of the experimental data base and the computer simulation. Better reliability and consistency in subject responses and a more accurate and responsive simulation would improve the prediction capability of the simulation.

Further studies should employ subjects proficient in the simulated aircraft. Since the results appeared to be strongly affected by the subjects' ability to repeat the task, use of experienced test pilots familiar with flight dynamics would help create a more reliable data base. Future research should include preliminary studies to determine other control parameters which when varied would create motion cues more significantly different. Discrete rating scale data is difficult to analyze with classic analysis of variance techniques, therefore, methods for obtaining pilot responses from a continuous, interval scale should be pursued.

Time did not allow for elimination of the inefficiencies of the simulation. Recomputation of the human dynamic orientation program's input and output model parameters would most likely improve the responsiveness of the model. Converting the program to double precision would reduce the inaccuracies, but double the computer memory requirements. The core required as listed in Appendix C and as executed on the IBM 360/67 Operating System was 458K. The entire flight

acceleration data set was read in at once. Other time histories, such as the simulation motion vectors, were computed creating large core requirements. If each time frame were processed through the simulation before the next was read in, the core requirements would be reduced by 75 percent.

It was assumed that an accurate facsimile of the simulator motion was generated by the drive program. Since the lead compensation network was bypassed in the simulation, follow-on studies should compare the output of the drive program with actual simulator motion histories. This is a possible source of considerable error.

The motion vectors for the simulator and aircraft could have been compared directly without use of the human dynamic orientation program. A similar analysis of the difference between these vectors would provide a way of validating Ormby's model. If the method incorporating the model correlated appreciably higher with subject ratings, a reasonable validation of the human dynamic orientation would be achieved.

APPENDIX A

INSTRUCTIONS TO SUBJECTS

A. PURPOSE OF THE EXPERIMENTS

The intent of this study is to analyze pilot response to varying degrees of simulator realism or fidelity. Subjective ratings by commercial pilots like yourself will help construct a mathematical model of the human process of comparing simulator motion characteristics with those of the simulated aircraft. Ultimately, our goals are to validate a model of human dynamic orientation and to optimize the drive programs of aircraft simulators.

B. TASKS

You will be asked to repeat two familiar tasks, each lasting from three to three and one half minutes. The first will be a basic airwork pattern, designed to employ the maneuvers common to operations in the terminal phase of flight. The second task is a full ILS approach to a wave-off. The basic airwork task will be repeated approximately fifty times, while the drive program parameters are varied to produce different degrees of fidelity. At the end of each task you will be asked to rate the characteristics of the motion using three rating scales discussed below, as well as provide your subjective opinion of the motion, task, etc. During subsequent sessions, you will rate the motion following the ILS approach task, repeated roughly the same number of times.

Each session will consist of approximately 12-15 flights and last no longer than 80 minutes. Detailed diagrams of each task will be available during the runs. Additional details will be provided before the sessions begin.

The simulated aircraft in this study is the F-15, a high performance, fighter aircraft. Although you probably have had no experience in the F-15 itself, your background in high performance type aircraft was a major consideration in your being selected as a pilot for this study.

C. USE OF THE RATING SCALES - OBJECTIVE RESPONSES

Each trial run will employ a different set of drive program parameters. A standard set of parameters will produce a "standard motion" which will be presented during the first run and every fourth run thereafter. Repetition of the standard motion will reinforce your perception of it, allowing you to make comparative evaluations of the trial runs. A typical sequence of 12 runs per session will be presented as follows:

Trial No. $\boxed{1}$ 2 3 4 $\boxed{5}$ 6 7 8 $\boxed{9}$ 10 11 12

where $\boxed{5}$ indicates that the fifth run of the session will be the "standard motion."

1. Component Rating Scale

Evaluate the linear (translational) and rotational components of the motion following each simulator run using the component rating scale. Rate the motion characteristics

based on the descriptive phrases provided at each level of the scale. These subjective descriptions should be used merely as an aid in your evaluations. Responses should reflect consideration of:

a. Response to Control Inputs - simulator reaction to movement or pressure on flight controls.

b. Motion Deficiencies - motion deviations from experienced or anticipated aircraft motion, not a result of control inputs (e.g. response to turbulence, oscillations, etc.).

c. Other - any other discrepancies in the motion dynamics which you detect and consider significant.

Your responses should be formulated in reference to the absolute scales as well as in comparison to your rating of the standard motion.

2. Comparative Rating Scale

Rate the trial runs in comparison the the standard motion using the comparative rating scale. Brief descriptions of each level of the scale should aid your evaluation.

3. Combined Rating Scale

Using the descriptive phrases on the component rating scale, rate the trial run on an overall or combined basis. Reference should be made to your scores given on both the component and comparative rating scales.

4. General

a. If you cannot choose between two adjacent levels on either of the scales, a "half" level score is allowed,

provided careful consideration is given to both adjacent levels.

b. Ensure that your rating of the "standard motion" is recorded on the scale and referred to while rating trial runs.

c. Basic performance measures will be recorded only during the ILS approaches. Although your performance will be compared to that of other pilots, our interest lies in how your performance varies with changes in fidelity.

d. Try to ignore changes in your performance on the task as each session progresses.

e. Your evaluations should reflect your assessment of all the motion cues detected.

D. SUBJECTIVE COMMENTS

After rating each trial run, brief comments on the items listed below are encouraged. It is not necessary to remark on each issue, but only on those you feel significant or particularly relevent to the trial run.

1. Your ability to rate, separately, the linear and rotational components of the motion.

2. Subjective description of the motion characteristics.

3. Difficulties encountered with the task as it is affected by the particular motion characteristics.

4. Impressions of the evaluation task.

5. Duration of the task versus your ability to evaluate the motion.

6. Physical discomfort (fatigue, nausea, etc.).

7. Workload level in terms of the attention level required to perform the task.

APPENDIX B

WASH-OUT FILTER PARAMETER SETS

Each wash-out filter (one for each degree of freedom) is described by three parameters. The values of the parameters used in the experiment are shown in Table B1. Where only one figure is shown, that value was used for all three channels. Natural frequencies for the translational channels are in the order of roll, pitch, and yaw. The parameters are defined as follows:

K_l - Linear gains for the translational channels

K_r - Linear gains for the rotational channels

w_l - Natural frequencies for the translational channels

w_r - Natural frequencies for the rotational channels

ζ_l - Damping factors for the translational channels

ζ_r - Damping factors for the rotational channels

The "standard motion" parameter set is denoted by P_0.

Parameter Set No.	K_l	K_r	w_l	w_r	ζ_l	ζ_r
P_0	0.5	0.5	.4 .4 1.0	1.2	.707	.707
P_1	0.3	0.3	.2 .2 .2	0.7	.707	.707
P_2	0.1	0.1	.4 .4 1.0	1.2	.707	.707
P_3	0.3	0.3	.2 .2 .7	1.6	.707	.707
P_4	1.0	0.1	.7 .7 1.5	0.7	.707	.707
P_5	1.0	0.1	.7 .7 1.5	1.2	.707	.707
P_6	1.0	0.1	.7 .7 1.5	1.6	.250	.707
P_7	0.7	0.3	.7 .7 1.5	1.2	.707	.707
P_8	0.1	1.0	.7 .7 1.5	1.6	.707	.707
P_9	0.3	0.7	.2 .2 .7	0.7	.707	.707
P_{10}	0.3	0.7	.2 .2 .7	1.2	.707	.707
P_{11}	0.1	1.0	.7 .7 1.5	0.7	.707	.707
P_{12}	0.1	1.0	.7 .7 1.5	1.2	.707	1.5
P_{13}	0.3	0.7	.7 .7 1.5	1.6	.707	.707
P_{14}	0.7	0.7	.7 .7 1.5	0.7	.707	.707
P_{15}	1.0	1.0	.4 .4 1.0	1.2	.707	.707

Table B1: Wash-out Parameter Sets Used in the Experiment

APPENDIX C

SIMULATION SOURCE PROGRAM LISTING

The simulation, written in FORTRAN IV H, consists of subroutines which perform the functions shown in the block diagram in Figure 9. The program listing in this appendix is in the configuration used to perform the experimental optimization described in section III.B.2. The main subroutine (called SIM) controls the other subroutines and prints the wash-out parameter set and messages displaying the progress of the program execution. A main program (not listed) reads in the values for the wash-out parameters, varies them, and iteratively calls the main subroutine. The flight acceleration time histories are read in by subroutines READ. The model parameters used by the human dynamic orientation program (subroutine HDO) are those obtained with the program listing contained in Ref. 21. The simulation was executed on an IBM 360/67 Operating System using single precision, floating point variables.

Subroutines MCPY and MINV are IBM system library subroutines called from subroutine COTRN to perform matrix operations. MCPY copies one array variable into another. MINV inverts a square matrix.

```
*****************************************************************
*                                                               *
*                       MAIN SUBROUTINE                         *
*                                                               *
*****************************************************************

C    PROGRAM TO EVALUATE THE SOFTWARE PARAMETERS OF THE S.01
C    MCTICN SIMULATOR USING THE ORMSBY HUMAN DYNAMIC
C    ORIENTATION MODEL
C
      SUBROUTINE SIM(CAD,CAVG,CRMS,K)
C
      COMMON/XFLOAT/TMT(3,3),TMR(3,3),BTACC(3),BRACC(3)
     *, TDDS(3),RSFX(3)
      CCMMON/IFIXED/IMODE,IDUMFU,IFORD,ICHG
      CCMMON/WSHOUT/AKR(3),AK1(3),OMGR(3),OMGT(3),ZETR(3)
     *, ZETT(3)
      CCMMON/FLIGHT/XA(4800,3),XR(4800,3),P,C,IPAR
C
      DIMENSION ACC(3),ROT(3),ANG(4800,3)
      DIMENSION SFS(4800,3),WS(4800,3),WA(4800,3)
C
      DATA DT/.05/,N/4800/
C
C    PRINT THE WASHOUT FILTER PARAMETERS
C
      WRITE(6,100)
100   FORMAT(1H0,'WASHOUT PARAMETERS READ FROM DATA FILE:')
C
      WRITE(6,120)(AKR(I),I=1,3)
      WRITE(6,121)(AK1(I),I=1,3)
      WRITE(6,122)(OMGR(I),I=1,3)
      WRITE(6,123)(OMGT(I),I=1,3)
      WRITE(6,124)(ZETR(I),I=1,3)
      WRITE(6,125)(ZETT(I),I=1,3)
C
C    READ THE FLIGHT DATA (AIRCRAFT MODEL OUTPUT)
C
      IF(K.GT.1) GO TO 131
      CALL READ(NSP)
C
      WRITE(6,109)
109   FORMAT('  FLIGHT DATA READ FROM TAPE FILE')
C
C    INITIALIZE THE INPUT ACCELERATIONS TO ZERO
C
131   BTACC(1)=0.
      BTACC(2)=0.
      BTACC(3)=-32.2
      BRACC(1)=0.
      BRACC(2)=0.
      BRACC(3)=0.
C
C    SET THE "FLAGS" FOR SUBROUTINE S01MOT
C
      IDUMFU=0
      IFCRD=0
      ICHG=1
C
C    SET THE MODE TO "INITIALIZE" AND CALL SUBROUTINE S01MOT
C
      IMODE=-1
      CALL S01MOT(DT)
C
      WRITE(6,101)
101   FORMAT('  SUBROUTINE S01MOT INITIALIZED')
C
C    SET THE MODE TO "RUN"
C
      IMODE=1
C
C    SET THE INPUT ACCELERATION SAMPLE AND CALL SUBROUTINE
```

```
C   S01MCT TO CREATE THE DRIVE COMMANDS
C
       DC 20 I=1,NSP
C
       BTACC(1)=XA(I,1)
       BTACC(2)=XA(I,2)
       BTACC(3)=XA(I,3)
       BRACC(1)=XR(I,1)
       BRACC(2)=XR(I,2)
       BRACC(3)=XR(I,3)
C
       CALL S01MOT(DT)
C
C   TRANSFORM THE DRIVE SIGNALS BACK INTO CAB (PILCT) COORDI-
C   NATES
C
       CALL COTRN(TDDS,TMT,1,ACC)
       CALL COTRN(RSFX,TMR,-1,ROT)
C
       SFS(I,1)=ACC(1)
       SFS(I,2)=ACC(2)
       SFS(I,3)=ACC(3)-32.2
       ANG(I,1)=ROT(1)
       ANG(I,2)=ROT(2)
       ANG(I,3)=ROT(3)
C
20     CCNTINUE
C
       WRITE(6,102)
102    FCRMAT('  SIMULATCR DRIVE SIGNALS CREATED')
C
C   DIFFERENTIATE THE ROTATIONAL POSITION COMMANDS TO OBTAIN
C   RCTATICNAL VELOCITY FOR USE BY THE HUMAN DYNAMIC
C   ORIENTATION (HDO) SUBROUTINE
C
       CALL DIFF(DT,ANG,WS,NSP,N)
C
       WRITE(6,103)
103    FCRMAT('  ROTATIONAL DRIVE SIGNALS DIFFERENTIATED')
C
C   CALL SUBROUTINE HDO TO COMPUTE THE PERCEIVED SIMULATOR
C   MOTICN VECTORS
C
       CALL HDO(DT,NSP,SFS,WS,9,N)
C
       WRITE(6,104)
104    FCRMAT('  PERCEIVED SIMULATCR MOTION VECTORS CREATED')
C
C   INTEGRATE THE RCTATIONAL FLIGHT ACCELERATION TO BE USED
C   BY SUBROUTINE HDO
C
       IF(K.GT.1) GO TO 132
       CALL INT(DT,XR,WA,NSP,N)
C
       WRITE(6,105)
105    FORMAT('  RCTATIONAL FLIGHT ACCELERATION INTEGRATED')
C
C   CALL SUBRCUTINE HDO TO COMPUTE THE PERCEIVED AIRCRAFT
C   MOTICN VECTORS
C
       CALL HDO(DT,NSP,XA,WA,8,N)
C
       WRITE(6,107)
107    FORMAT('  PERCEIVED FLIGHT MOTION VECTORS CREATED')
C
C   CPERATE THE COST ANALYSIS ROUTINE
C
132    CALL CCST(CAD,CAVG,CRMS)
C
       WRITE(6,108)
108    FCRMAT(1H0,' COST ROUTINE COMPLETE')
C
```

```
C   FCRMAT STATEMENTS
C
120     FORMAT(/5X,'AKR(1,2,3)  = ',3F6.3)
121     FCRMAT(5X,'AK1(1,2,3)  = ',3F6.3)
122     FCRMAT(5X,'OMGR(1,2,3) = ',3F6.3)
123     FCRMAT(5X,'OMGT(1,2,3) = ',3F6.3)
124     FCRMAT(5X,'ZETR(1,2,3) = ',3F6.3)
125     FORMAT(5X,'ZETT(1,2,3) = ',3F6.3/)
C
        RETURN
        END


*********************************************************************
*                                                                   *
*                          SUBROUTINES                              *
*                                                                   *
*********************************************************************

C   SUBRCUTINE TO INTEGRATE THE TIME SERIES CONSISTING OF THE
C   RCTATIONAL FLIGHT ACCELERATION (AIRCRAFT MODEL OUTPUT)
C
        SUBROUTINE INT(H,Y,Z,NSP,N)
C
        DIMENSION Y(N,3),Z(N,3)
C
        HT=.3333333*H
        DO 7 J=1,3
        SUM1=Y(2,J)+Y(2,J)
        SUM1=SUM1+SUM1
        SUM1=HT*(Y(1,J)+SUM1+Y(3,J))
        AUX1=Y(4,J)+Y(4,J)
        AUX1=AUX1+AUX1
        AUX1=SUM1+HT*(Y(3,J)+AUX1+Y(5,J))
        AUX2=HT*(Y(1,J)+3.875*(Y(2,J)+Y(5,J))+2.625*(Y(3,J)+
       *Y(4,J))+Y(6,J))
        SUM2=Y(5,J)+Y(5,J)
        SUM2=SUM2+SUM2
        SUM2=AUX2-HT*(Y(4,J)+SUM2+Y(6,J))
        Z(1,J)=0.
        AUX=Y(3,J)+Y(3,J)
        AUX=AUX+AUX
        Z(2,J)=SUM2-HT*(Y(2,J)+AUX+Y(4,J))
        Z(3,J)=SUM1
        Z(4,J)=SUM2
C
        DO 4 I=7,NSP,2
        SUM1=AUX1
        SUM2=AUX2
        AUX1=Y(I-1,J)+Y(I-1,J)
        AUX1=AUX1+AUX1
        AUX1=SUM1+HT*(Y(I-2,J)+AUX1+Y(I,J))
        Z(I-2,J)=SUM1
        IF(I-NSP)3,6,6
      3 AUX2=Y(I,J)+Y(I,J)
        AUX2=AUX2+AUX2
        AUX2=SUM2+HT*(Y(I-1,J)+AUX2+Y(I+1,J))
        Z(I-1,J)=SUM2
      4 CONTINUE
      5 Z(NSP-1,J)=AUX1
        Z(NSP,J)=AUX2
        GO TO 7
      6 Z(NSP-1,J)=SUM2
        Z(NSP,J)=AUX1
      7 CONTINUE
C
        RETURN
        END
```

```
C   SUBROUTINE TO PRODUCE THE SIMULATOR DRIVE SIGNALS FROM
C   THE FLIGHT DATA OBTAINED FROM THE MAIN PROGRAM
C
      SUBROUTINE S01MOT(DT)
C
C           MOTION DRIVE SYSTEM FOR S.01 (SIX-DEGREE)
C
C           PREPARED BY J.DOUVILLIER (NASA)        3 SEPT 1975
C           PROGRAMMED BY D.ASTILL    (CSC)       12 SEPT 1975
C           MODIFIED BY DATA ANALYSIS GROUP (CSC)    DEC 1976
C
      COMMON/XFLOAT/TMT(3,3),TMR(3,3),BTACC(3),BRACC(3)
     *, TDDS(3),RSFX(3)
      COMMON/IFIXED/IMODE,IDUMFU,IFORD,ICHG
      COMMON/WSHOUT/AKR(3),AK1(3),OMGR(3),OMGT(3),ZETR(3)
     *, ZETT(3)
      COMMON/MOTION/OMGRL(3),OMGRQ(3),OMGRE(3),OMGTE(3)
     1, ZETAQ(3),ZETRL(3),ZDLF(3),GNRS(3),AKRL(3),SOMGR(3)
     2, ZOMGR(3),OMGQSQ(3),TOMGRE(3),OMGRE2(3),OMGT2(3)
     3, TOMZT(3),FOMGTE(3),SOMGT2(3),FOMGT3(3),OMGTE4(3)
     4, CMGTQ(3),GLEAD(3)
C
      DIMENSION RPOSL(3),TPOSL(3),TMS(3),RAC(3),TAC(3)
     1,FNOT(3),TDCSI(3),TDCSII(3),FNCHI(3),FNCHII(3)
     2,RHFI(3),RHFII(3),RDHI(3),RCH(3),RDH(3),FNA(3)
     3,RHFFB(3),RDLI(3),RLF(3),RL(3),RSF(3),RDM(3),RDCH(3)
     4,FCF(3),RHF(3),RS(3),RIC(3),TIC(3),RSD(3),FNCL(3)
     5,TDSC(3),FCHI(3),FKN(3),FNAS(3),FNCH(3),FNCHTP(3)
     6,TDDH(3),TDDT(3),ADDL(3),TDS(3),TSIL(3),TDCSP(3)
     7,TDDA(3),TDDG(3),TSD(3),AFU(6),ADSD(6),KFLAG(3)
     8,FOLUPS(6),GNH(3),AIC(6)
C
      EQUIVALENCE (FOLUPS(1),AFU(1))
      EQUIVALENCE (ADSD(1),TSD(1))
C
      DATA G/32.2/,RG/.031056/
      DATA TDDG/0.,0.,-32.2/
      DATA FNOT/3*1./
      DATA TIC/3*0./,RIC/3*0./
      DATA ADDL/5.6,6.8,5.5/
      DATA GNH/3*1.0/
      DATA AKXL/1./
      DATA AKYL/1./
      DATA RPOSL/3*.5326/
      DATA TPOSL/3*8./
      DATA NORES/0/
C                                        FAST SINE AND COSINE APPROX.
      XCOS(X)=1.-(X*X)/2.
      XSIN(X)=X-(X**3)/6.
C
      IF(IMODE)10,60,100
C                                       CLEAR LIMIT FLAGS, INITIALIZE
C                                       FILTERS, AND ZERO DRIVES
10    DO 20 IN=1,3
C
      KFLAG(IN)=0
      FOLUPS(IN)=0.
      FOLUPS(IN+3)=0.
      ADSD(IN)=0.
      ADSD(IN+3)=0.
      RLF(IN)=0.
      TSD(IN)=0.
      TSIL(IN)=0.
      RCH(IN)=0.
      RL(IN)=0.
      RDHI(IN)=0.
      RHFFB(IN)=0.
      DTP=0.
C
      CPHSF=1.
      CTHSF=1.
      CPSSF=1.
```

```
      SPHSF=0.
      STHSF=0.
      SPSSF=0.
      CPHLF=1.
      CTHLF=1.
      CPSLF=1.
      SPHLF=0.
      STHLF=0.
      SPSLF=0.
C
      TMS(IN)=.5/ADDL(IN)
C
   20 CONTINUE
C                                                UPDATE FILTERS IF ICHG=1
C                                                OR DT CHANGED
      IF(ICHG.EQ.1) GO TO 25
      IF(DTP-DT) 24,100,24
   24 ICHG=1
   25 DTP=DT
      CALL SO1MIC(DTP)
      ICHG=0
C                                      COMPUTE FOLLOW UP IF NO CAB MOTION
100   DO 53 J=1,6
      IF(IDUMFU.EQ.0) GO TO 51
      AFU(J)=ADSD(J)
      FOLUPS(J)=ADSD(J)
      GO TO 53
   51 AFU(J)=FOLUPS(J)
   53 CONTINUE
C
      FNATS=0.
      DO 200 IR=1,3
C                                                  COMPUTE LOAD FACTORS
      FNA(IR)= BTACC(IR)*RG
      FNAS(IR)=FNA(IR)*FNA(IR)
      FKN(IR)=AK1(IR)*FNA(IR)
      FNATS=FNATS+FNAS(IR)
C                                                    ROTATIONAL WASHOUT
      RDM(IR)=AKR(IR)*BRACC(IR)
      RDCH(IR)=RDM(IR)-ZOMGR(IR)*RCH(IR)-SOMGR(IR)*RHFFB(IR)
C
      RCH(IR)=RCH(IR)+RDCH(IR)*DT
C
  200 CONTINUE
C                                              ROTATIONAL (CAB TO GIMBAL)
C                                                    TRANSFORMATION
C                                                        MATRIX
      TMR(1,1)=1.
      TMR(1,2)=-CPHSF*SPSSF/CPSSF
      TMR(1,3)=SPHSF*SPSSF/CPSSF
      TMR(2,1)=0.
      TMR(2,2)=CPHSF/CPSSF
      TMR(2,3)=-SPHSF/CPSSF
      TMR(3,1)=0.
      TMR(3,2)=SPHSF
      TMR(3,3)=CPHSF
C
      RDH(1)=RCH(1)+RCH(2)*TMR(1,2)+RCH(3)*TMR(1,3)
      RDH(2)=RCH(2)*TMR(2,2)+RCH(3)*TMR(2,3)
      RDH(3)=RCH(2)*TMR(3,2)+RCH(3)*TMR(3,3)
C
      FNAT=SQRT(FNATS)
C
      IF(FNAT.EQ.0.) FNAT=1.0
C
      FNMXL=FKN(1)*AKXL/FNAT
      FNMYL=FKN(2)*AKYL/FNAT
      FNMZL  =-SQRT(1.-FNMXL*FNMXL-FNMYL*FNMYL)
C
C                                              LOW FREQ RESIDUAL TILT RATE
C
      RDLI(1)=(-FNMXL*( SPSLF*CTHLF)/CPSLF -FNMYL*CPHLF*CTHLF
```

```
     *          +FNMZL*SPHLF*CTHLF)
      RDLI(2)=(FNMXL*CTHLF/CPSLF  +FNMYL*SPHLF*STHLF
     *          +FNMZL*CPHLF*STHLF)
      RDLI(3)=(-FNMXL*SPSLF*STHLF-FNMYL*CPHLF*CPSLF*STHLF
     *          +FNMZL*SPHLF*CPSLF*STHLF)
C
      DO 250  IR=1,3
C
      RHFFB(IR)=RHFFB(IR)+RDH(IR)*DT
      IF(IMODE.LT.0) RDLI(IR)=0.
      RL(IR)=RL(IR)+RDLI(IR)*DT
      RDLR=ZDLF(IR)*(RL(IR)*AKRL(IR)-RLF(IR))
      RLF(IR)=RLF(IR)+RDLR
      IF(NORES.EQ.1)RLF(IR)=0.
      RDHI(IR)=RDHI(IR)+RDH(IR)*DT
C
      IF(IMODE.GE.0) GO TO 245
      RDHI(IR)=RDH(IR)
      RHFI(IR)=0.
      RHFII(IR)=(RDHI(IR)*GNRS(IR))/OMGRE2(IR)
  245 CONTINUE
      RHF(IR)=RDHI(IR)*GNRS(IR)-TOMGRE(IR)*RHFI(IR)
     *         -OMGRE2(IR)*RHFII(IR)
      RHFI(IR)=RHFI(IR)+RHF(IR)*DT
      RHFII(IR)=RHFII(IR)+RHFI(IR)*DT
C
C                                          ROTATIONAL  POSITION  LIMIT
C
      RSF(IR)=RLF(IR)+RHF(IR)+RIC(IR)
      RSFX(IR)=RSF(IR)
      IF(ABS(RSFX(IR)).GT.RPOSL(IR)) RSFX(IR)=SIGN(RPOSL(IR)
     *,RSFX(IR))
C                                ROTATIONAL  POSITION  COMMAND  OUTPUT
C
      RSD(IR)=RSF(IR)+RDH(IR)/OMGRQ(IR)
      IF(ABS(RSD(IR)).GT.RPOSL(IR)) RSD(IR)=SIGN(RPOSL(IR)
     *,RSD(IR))
C
  250 CONTINUE
C
      CPHLF=XCOS(RLF(1))
      SPHLF=XSIN(RLF(1))
      CTHLF=XCOS(RLF(2))
      STHLF=XSIN(RLF(2))
      CPSLF=XCOS(RLF(3))
      SPSLF=XSIN(RLF(3))
      CPHSF=XCOS(RSF(1))
      SPHSF=XSIN(RSF(1))
      CTHSF=XCOS(RSF(2))
      STHSF=XSIN(RSF(2))
      CPSSF=XCOS(RSF(3))
      SPSSF=XSIN(RSF(3))
C                              TRANSLATIONAL  (CAB  TO  LINEAR  DRIVE)
C                                          TRANSFORMATION
C                                             MATRIX
      TMT(1,1)=CPSSF*CTHSF
      TMT(2,1)=SPSSF
      TMT(3,1)=-CPSSF*STHSF
      TMT(1,2)=-CPHSF*SPSSF*CTHSF+SPHSF*STHSF
      TMT(2,2)=CPHSF*CPSSF
      TMT(3,2)=CPHSF*SPSSF*STHSF+SPHSF*CTHSF
      TMT(1,3)=SPHSF*SPSSF*CTHSF+CPHSF*STHSF
      TMT(2,3)=-SPHSF*CPSSF
      TMT(3,3)=-SPHSF*SPSSF*STHSF+CPHSF*CTHSF
C
      FNCL(1)=STHLF*CPSLF
      FNCL(2)=-CPHLF*STHLF*SPSLF-SPHLF*CTHLF
      FNCL(3)=SPHLF*STHLF*SPSLF-CPHLF*CTHLF
C
      FCHI(1)=FKN(1)-FNCL(1)/AKXL
      FCHI(2)=FKN(2)-FNCL(2)/AKYL
      FCHI(3)=FKN(3)
```

```
C
      DO 270 IT=1,3
C
      IF(IMODE.GE.0) GO TO 267
      FNCHI(IT)=0.
      FNCHII(IT)=(FCHI(IT)*GNH(IT))/OMGT2(IT)
  267 CONTINUE
      FNCH(IT)=GNH(IT)*FCHI(IT)-TOMZT(IT)*FNCHI(IT)-
     * CMGT2(IT)*FNCHII(IT)
      FNCHI(IT)=FNCHI(IT)+FNCH(IT)*DT
      FNCHII(IT)=FNCHII(IT)+FNCHI(IT)*DT
      TDDH(IT)=G*(FNCH(IT)+FNCL(IT))
C
  270 CONTINUE
C
      DO 300 IT=1,3
C
      TDDA(IT)=0.
C
      DO 280 JT=1,3
C
      TDDA(IT)=TDDA(IT)+TDDH(JT)*TMT(IT,JT)
  280 CONTINUE
      TDDT(IT)=(TDDA(IT)-TDDG(IT))*FNOT(IT)
C                                                   DUMMY FOLLOW-UPS
      IF(IDUMFU.EQ.1) FOLUPS(IT)=TSD(IT)
C
C                     CHECK OPERATING AREA......PARABOLIC LIMIT?
C
      IF(FOLUPS(IT)*TSIL(IT)) 283,283,282
  282 ZTEMP=TSIL(IT)*TSIL(IT)*TMS(IT)
      IF((TPOSL(IT)-ABS(TSD(IT))).GE.ZTEMP) GO TO 283
      KFLAG(IT)=1
      TDDT(IT)=-SIGN(ADDL(IT),FOLUPS(IT))
      GO TO 294
  283 IF(KFLAG(IT).EQ.0) GO TO 294
      IF(FOLUPS(IT)*TDDT(IT)) 286,286,285
  285 TDDT(IT)=0.
      GO TO 294
  286 KFLAG(IT)=0
  294 CONTINUE
C
      IF(ABS(TDDT(IT)).GT.ADDL(IT)) TDDT(IT)=SIGN(ADDL(IT)
     *,TDDT(IT))
C
      IF(IMODE) 295,297,297
  295 CONTINUE
      TSIL(IT)=0.
      TDCSP(IT)=0.
      TDCSI(IT)=0.
      TDCSII(IT)=TDDT(IT)/OMGTE4(IT)
  297 CONTINUE
      TDDS(IT)=TDDT(IT)-FOMGTE(IT)*TSIL(IT)-SOMGT2(IT)*
     * TDCSP(IT)-FOMGT3(IT)*TDCSI(IT)-OMGTE4(IT)*TDCSII(IT)
      TSIL(IT)=TSIL(IT)+TDDS(IT)*DT
      TDCSP(IT)=TDCSP(IT)+TSIL(IT)*DT
      TDCSI(IT)=TDCSI(IT)+TDCSP(IT)*DT
      TDCSII(IT)=TDCSII(IT)+TDCSI(IT)*DT
C
C                            TRANSLATIONAL POSITION COMMAND OUTPUT
C                            AND LEAD COMPENSATION
C
      TSD(IT)=TDDS(IT)*OMGQSQ(IT)+TSIL(IT)*GLEAD(IT)+
     * TDCSP(IT)+TIC(IT)
C
  300 CONTINUE
C
  60  CONTINUE
C
      RETURN
      END
```

```
C   SUBROUTINE TO INITIALIZE THE FILTER PARAMETERS FOR
C   THE DRIVE PROGRAM (SUBROUTINE SO1MOT)
C
       SUBROUTINE SO1MIC(DTP)
C
C            PROGRAMMED BY D. ASTILL    (CSC)       12 SEPT 1975
C
       COMMON/WSHOUT/AKR(3),AK1(3),OMGR(3),OMGT(3),ZETR(3)
      *, ZETT(3)
C
       COMMON/MOTION/OMGRL(3),OMGRQ(3),OMGRE(3),OMGTE(3)
      1, ZETAQ(3),ZETRL(3),ZDLF(3),GNRS(3),AKRL(3),SOMGR(3)
      2, ZOMGR(3),OMGQSQ(3),TOMGRE(3),OMGRE2(3),OMGT2(3)
      3, TOMZT(3),FOMGTE(3),SOMGT2(3),FOMGT3(3),OMGTE4(3)
      4, OMGTQ(3),GLEAD(3)
C
       DO 200 IN=1,3
C
       AKRL(IN)=OMGRL(IN)/(2.*ZETRL(IN))
       SOMGR(IN)=OMGR(IN)**2
       ZOMGR(IN)=2.*OMGR(IN)*ZETR(IN)
       OMGQSQ(IN)=1./OMGTQ(IN)**2
       GLEAD(IN)=2.*ZETAQ(IN)/OMGTQ(IN)
       TOMGRE(IN)=2.*OMGRE(IN)
       OMGRE2(IN)=OMGRE(IN)**2
       OMGT2(IN)=OMGT(IN)**2
       TOMZT(IN)=2.*OMGT(IN)*ZETT(IN)
       FOMGTE(IN)=4.*OMGTE(IN)
       SOMGT2(IN)=6.*OMGTE(IN)**2
       FOMGT3(IN)=4.*OMGTE(IN)**3
       OMGTE4(IN)=OMGTE(IN)**4
       ZDLF(IN)=1.-EXP(-DTP*2.*ZETRL(IN)*OMGRL(IN))
C
   200 CONTINUE
C
       RETURN
       END


C   BLOCK DATA SUBPROGRAM TO INITIALIZE THE NON-WASHOUT
C   FILTER PARAMETERS
C
       BLOCK DATA
C
       COMMON/MOTION/OMGRL(3),OMGRQ(3),OMGRE(3),OMGTE(3)
      1, ZETAQ(3),ZETRL(3),ZDLF(3),GNRS(3),AKRL(3),SOMGR(3)
      2, ZOMGR(3),OMGQSQ(3),TOMGRE(3),OMGRE2(3),OMGT2(3)
      3, TOMZT(3),FOMGTE(3),SOMGT2(3),FOMGT3(3),OMGTE4(3)
      4, OMGTQ(3),GLEAD(3)
C
       DATA ZETRL/3*.707/,ZETAQ/.7,.7,50./
       DATA GNRS/3*1./,OMGRL/3*1.2/,OMGRQ/8.5,7.,8.5/
       DATA OMGTQ/4.1,7.,130./,OMGTE/3*.05/
       DATA OMGRE/3*.01/
C
       END
```

```
C   ORMSBY HUMAN DYNAMIC ORIENTATION MODEL SUBROUTINE
C
       SUBROUTINE HDO(XDT,NSP,SF,W,IOUT,N)
C
       DIMENSION TC(4,4),TO(3,3),TPC(3,3),TPO(2,2),CC(4)
      1,CO(3),XCH(4),YCH(4),ZCH(4),CS(3),XOH(3),YOH(3),ZOH(3)
      2,XC(3),YC(3),ZC(3),XO(2),GKO(3),GKS(3),ZO(3),CTC(3,3)
      3,CTO(3,3),A(3),GKC(4),TWH(3),TAH(3),TWS(3),TAS(3)
      4,AO(3),WO(3),EWS(3),EWH(3),EAH(3),EAS(3),WNCO(3)
      5,WNCL(3),VO(3),DVC(3),DVO(2),WOF(3),YO(3),DCLD(3)
      6,WSFO(3),FN(3),Y(3)
       DIMENSION W(N,3),SF(N,3)
C
       DATA DT/1.0/,NITP/10/
C
       REWIND IOUT
       REWIND 4
C
       NDT=NSP*DT/NITP
       INDT=(NDT-2)/2
       WRITE(IOUT,400)DT,INDT
C
C   CANAL SPECIFICATIONS.
       DO 10 I=1,4
       READ(4,530)  TC(I,1),TC(I,2),TC(I,3),TC(I,4)
 10    CONTINUE
       DO 15 I=1,3
       READ(4,530)  TPC(I,1),TPC(I,2),TPC(I,3),DVC(I)
 15    CONTINUE
       READ(4,530)  CC(1),CC(2),CC(3),CC(4)
       READ(4,530)  GKC(1),GKC(2),GKC(3),GKC(4)
       READ(4,550)  FSCC,TSCC,SSCC
       CALL EULER(FSCC,TSCC,SSCC,CTC)
C
C   OTOLITH SPECIFICATIONS.
       DO 20 I=1,3
       READ(4,550)  TO(I,1),TO(I,2),TO(I,3)
 20    CONTINUE
       DO 25 I=1,2
       READ(4,550)  TPO(I,1),TPO(I,2),DVO(I)
 25    CONTINUE
       READ(4,550)CO(1),CO(2),CO(3)
       READ(4,570)  GKO(1),GKO(2),GKO(3),GKS(1),GKS(2),GKS(3)
       READ(4,570)  FOTO,TOTO,SOTO,SACFAC,OSPG,DFAC
       CALL EULER(FOTO,TOTO,SOTO,CTO)
       DO 27 I=1,3
       CS(I)=CO(I)*SACFAC
 27    CONTINUE
C
C   INITIALIZATION
       DO 32 I=1,4
       READ(4,550)XCH(I),YCH(I),ZCH(I)
 32    CONTINUE
       A(1)=XCH(4)
       A(2)=YCH(4)
       A(3)=ZCH(4)
       CALL COTRN(A,CTC,1,WO)
       DO 36 I=1,3
       READ(4,550)  XOH(I),YOH(I),ZOH(I)
 36    CONTINUE
       A(1)=XOH(3)
       A(2)=YOH(3)
       A(3)=ZOH(3)
       CALL COTRN(A,CTO,1,AO)
       DO 45 I=1,3
       READ(4,540)XC(I),YC(I),ZC(I),WNCO(I),WNCL(I)
 45    CONTINUE
       DO 50 I=1,2
       READ(4,550)  XO(I),YO(I),ZO(I)
 50    CONTINUE
       READ(4,550)DOLD(1),DOLD(2),DOLD(3)
       READ(4,550)WSFO(1),WSFO(2),WSFO(3)
```

```
      READ(4,550)WOF(1),WOF(2),WOF(3)
      READ(4,580) TDVEL,TDPOS,TNC,FNOISE
      FP=1.0-EXP(-DT/TDPOS)
      FD=TDVEL
      FN(1)=EXP(-DT/TNC)
      FN(2)=TNC*(1.-FN(1))/DT-FN(1)
55    FN(3)=1.-TNC*(1.-FN(1))/DT
C
C  MAIN PROGRAM CYCLE.
C
C     COMPUTE CURRENT STIMULUS IN HEAD COORDINATES
C     (EVERY DT/NITP SEC.)
C      1. ANGULAR ROTATION VECTOR (TWH) AT (TIME).
C      2. SPECIFIC FORCE VECTOR (TAH) AT (TIME+DT/2)
C      3. TRUE DOWN VECTOR AT (TIME+DT/2).
C
      DO 450 ITIME=1,INDT
      DO 100 I=1,NITP
      TIME=(ITIME-1)*DT+I*DT/NITP
C
      J=20.*TIME+1.5
      K=J+10
C
      TAH(1)=SF(K,1)/32.2
      TAH(2)=SF(K,2)/32.2
      TAH(3)=SF(K,3)/32.2
      TWH(1)=W(J,1)
      TWH(2)=W(J,2)
      TWH(3)=W(J,3)
C
C    TRANSFORM TO SENSOR COORDINATES.
      CALL COTRN(TWH,CTC,0,TWS)
      CALL COTRN(TAH,CTO,0,TAS)
C
C    SENSOR STIMULATION (EVERY DT/NITP SEC.):
C      USING CURRENT STIMULUS VALUES, UPDATE STATE VECTORS
C       FOR 3 CANALS (XC, YC, AND ZC), AND 3 OTOLITHS
C       (XO, YO, ZO), AND COMPUTE AFFERENT FIRING RATES
C       (CSX, CSY, CSZ).
C
      S=TWS(1)
      CALL SVUPD(XC,TPC,DVC,S,CSX,CC,3,4)
      S=TWS(2)
      CALL SVUPD(YC,TPC,DVC,S,CSY,CC,3,4)
      S=TWS(3)
      CALL SVUPD(ZC,TPC,DVC,S,CSZ,CC,3,4)
      S=TAS(1)
      CALL SVUPD(XO,TPO,DVO,S,OSX,CO,2,3)
      S=TAS(2)
      CALL SVUPD(YO,TPO,DVO,S,OSY,CO,2,3)
      S=TAS(3)
  100 CALL SVUPD(ZO,TPO,DVO,S,OSZ,CS,2,3)
C
C    OPTIMAL ESTIMATOR (UPDATE EVERY DT SEC.):
C      GET CANAL AND OTOLITH SYSTEM, STATE ESTIMATES FROM
C       STEADY STATE KALMAN FILTERS.
C
      CALL SSKF(XCH,CSX,TC,CC,GKC,4)
      CALL SSKF(YCH,CSY,TC,CC,GKC,4)
      CALL SSKF(ZCH,CSZ,TC,CC,GKC,4)
      CALL SSKF(XOH,OSX,TO,CO,GKO,3)
      CALL SSKF(YOH,OSY,TO,CO,GKO,3)
      CALL SSKF(ZOH,OSZ,TO,CS,GKS,3)
C
C    ENTER ROTATION RATE ESTIMATE VECTOR (CANAL ESTIMATE).
      EWS(1)=XCH(4)
      EWS(2)=YCH(4)
      EWS(3)=ZCH(4)
C
C    ENTER SPECIFIC FORCE ESTIMATE VECTOR (OTOLITH ESTIMATE)
      EAS(1)=XOH(3)
      EAS(2)=YOH(3)
```

```
C
C     SACCULE NON-LINEARITY.
       EAS(3)=AMAX1(.6*(ZOH(3)+.4169)-.4169,-.4169)
C
C     RESTORE MAGNITUED OF OTOLITH ESTIMATE TO VALUE HELD
C     BEFORE CONSIDERATION OF SACCULE NON-LINEARITY.
C     (THEREFORE, NON-LINEARITY EFFECTS ONLY DIRECTION OF
C     THE OTOLITH ESTIMATE).
C
       CALL NORM(EAS,Y)
       DO 130 I=1,3
  130  EAS(I)=Y(I)*SQRT(XOH(3)**2+YOH(3)**2+ZOH(3)**2)
C
C     TRANSFORM TO HEAD COORDINATES
       CALL COTRN(EWS,CTC,1,EWH)
       CALL COTRN(EAS,CTO,1,EAH)
C
C     DOWN AND W ESTIMATOR (UPDATE EVERY DT SECONDS).
C     COMBINE OTOLITH AND CANAL ESTIMATES TO FORM NEW
C     ESTIMATE OF:
C       1. PERCEIVED DOWN (DNEW) AT (TIME+DT/2).
C       2. PERCEIVED ACCELERATION (ACC) AT (TIME+DT/2).
C       3. PERCEIVED ANGULAR VELOCITY (WTOT) AT (TIME).
C
  440 CALL DOWN(DOLD,EWH,EAH,AO,WSFO,FD,CT,TDPOS,DFAC,WOF
     *, WNCO,WNCL,FN,IOUT)
C
  450 CONTINUE
C
C   FORMAT STATEMENTS.
C
  400 FORMAT(F6.3,I4)
  520 FORMAT(E15.8,I5)
  530 FORMAT(4E15.8)
  540 FORMAT(5E15.8)
  550 FORMAT(3E15.8)
  570 FORMAT(6E12.5)
  580 FORMAT(4E15.8 )
C
      RETURN
      END




C   DOWN ESTIMATOR AND W ESTIMATOR
C
      SUBROUTINE DOWN(DOLD,WN,SN,SO,WSFO,T,DT,TDPS,DFAC,WOF
     *, WNCO,WNL,FN,IOUT)
C
C   DOWN IS DETERMINED BY RELYING ON LOW FREQUENCY OTOLITH
C   ESTIMATES, CANAL ESTIMATES THAT ARE CONSISTENT WITH
C   HIGH FREQUENCY OTOLITH ESTIMATES, AND THE HIGH FREQUENCY
C   PORTION OF CANAL ESTIMATES NOT CONFIRMED BY OTOLITHS.
C
C   W IS DETERMINED BY CANAL ESTIMATES PARELLEL TO DOWN,
C   ROTATION RATE OF DOWN, AND HIGH FREQUENCY PORTION OF
C   CANAL ESTIMATES PERPENDICULAR TO DOWN MINUS ROTATION
C   RATE OF DOWN.
C
      DIMENSION DOLD(3),WN(3),SN(3),SO(3),WSFO(3),F(3)
     1,X(3),WOF(3),RSCC(3),RCTO(3),RTOT(3),DNEW(3),RPOS(3)
     2,WPERP(3),DAVG(3),WPARE(3),WTOT(3),ACC(3),ANG(3)
     3,WNCO(3),WNL(3),FN(3),WNC(3),WNCH(3),HROTO(3),WSF(3)
     4,WCO(3),WODN(3)
C
      SFMAG=SQRT(SN(1)*SN(1)+SN(2)*SN(2)+SN(3)*SN(3))
      FPOS=1.0-EXP(-((SFMAG/DFAC)**(.25))*DT/TDPS)
      TDVEL=T
      F(1)=EXP(-DT/TDVEL)
```

```
      F(2)=TDVEL*(1.-F(1))/DT-F(1)
      F(3)=1.-TDVEL*(1.-F(1))/DT
      CALL CROSS(SO,SN,WSF)
      CALL NORM(WSF,X)
      CALL VANG(SO,SN,ANGSF)
      DO 10 I=1,3
      WSF(I)=ANGSF*X(I)
      WOF(I)=F(1)*WOF(I)+F(2)*WSFO(I)+F(3)*WSF(I)
      WOD(I)=WSF(I)-WOF(I)
   10 WSFO(I)=WSF(I)
      WODM=SQRT(WOD(1)*WOD(1)+WOD(2)*WOD(2)+WOD(3)*WOD(3))
      CALL NORM(WOD,WODN)
      WCPWD=WN(1)*WODN(1)+WN(2)*WODN(2)+WN(3)*WODN(3)
      IF(WCPWD) 12,12,11
   11 WCPWD=0.0
   12 WMAG=-WCPWD*DT
      DO 13 I=1,3
      X(I)=WODN(I)*AMIN1(WMAG,WODM)
      WNC(I)=-WN(I)*DT-X(I)
      WNL(I)=FN(1)*WNL(I)+FN(2)*WNCO(I)+FN(3)*WNC(I)
      WNCO(I)=WNC(I)
      WNCH(I)=WNC(I)-WNL(I)
   13 X(I)=X(I)+WNCH(I)
      CALL CROSS (DOLD,SN,ROTO)
      CALL NORM(ROTO,F)
      WOPARM=WOF(1)*F(1)+WOF(2)*F(2)+WOF(3)*F(3)
      DO 15 I=1,3
      ROTO(I)=WOPARM*F(I)
   15 HROTO(I)=ROTO(I)/2.
      CALL ROTATE(DOLD,HROTO,F)
      WCPARM=X(1)*F(1)+X(2)*F(2)+X(3)*F(3)
      DO 20 I=1,3
      RSCC(I)=(X(I)-WCPARM*F(I))
   20 RTOT(I)=RSCC(I)+ROTO(I)
      CALL ROTATE(DOLD,RTOT,DNEW)
      CALL VANG(DNEW,SN,FEE)
      PHI=FPOS*FEE
      CALL CROSS(DNEW,SN,RPOS)
      CALL NORM(RPOS,X)
      DO 30 I=1,3
   30 RPOS(I)=PHI*X(I)
      CALL ROTATE(DNEW,RPOS,X)
      CALL NORM(X,DNEW)
      DO 40 I=1,3
   40 X(I)=DOLD(I)+DNEW(I)
      CALL NORM(X,DAVG)
      WPARM=WN(1)*DAVG(1)+WN(2)*DAVG(2)+WN(3)*DAVG(3)
      CALL CROSS(DNEW,DOLD,WPERP)
      CALL NORM(WPERP,X)
      CALL VANG(DOLD,DNEW,PHI)
      DO 50 I=1,3
      WPERP(I)=X(I)*PHI/DT
      WPARE(I)=WPARM*DAVG(I)
      DOLD(I)=DNEW(I)
      SO(I)=SN(I)
      WTOT(I)=WPERP(I)+WPARE(I)
      ACC(I)=DFAC*DNEW(I)-SN(I)
   50 CONTINUE
   45 WRITE(IOUT,100)ACC(1),ACC(2),ACC(3),WTOT(1),WTOT(2)
     *,WTOT(3),DNEW(1),DNEW(2),DNEW(3)
  100 FORMAT(9E14.7)
C
      RETURN
      END
```

```
C   SUBROUTINE TO DEVELOP A COST ALGORITHM BASED ON THE
C   DIFFERENCE BETWEEN THE PERCEPTION OF SIMULATOR AND
C   AIRCRAFT MOTION
C
      SUBROUTINE COST(CAD,CAVG,CRMS)
C
      COMMON/FLIGHT/XA(4884,3),XR(4884,3),P,C,IPAR
C
      DIMENSION AA(3),AS(3),WA(3),WS(3),DWNA(3),DWNS(3)
      DATA WTH,ATH/.0146,.005/
C
      CAVG=0.
      CRMS=0.
      CAD=0.
C
      CWAV=0.
      CAAV=0.
      CDAV=0.
C
      CWRMS=0.
      CARMS=0.
      CDRMS=0.
C
      ADW=0.
      ADA=0.
      ADD=0.
C
C   READ IN THE DATA FROM THE TWO FILES
C
      REWIND 9
      REWIND 8
C
      READ(9,30)DTS,NSS
      READ(8,30)DTA,NSA
C
C   COMPUTATION OF THE COST ESTIMATION VALUES
C
      DO 40 I=1,NSA
C
      READ(9,10)AS(1),AS(2),AS(3),WS(1),WS(2),WS(3),DWNS(1)
     *,DWNS(2),DWNS(3)
      READ(8,10)AA(1),AA(2),AA(3),WA(1),WA(2),WA(3),DWNA(1)
     *,DWNA(2),DWNA(3)
C
      DW1=WA(1)-WS(1)
      DW2=WA(2)-WS(2)
      DW3=WA(3)-WS(3)
C
      DA1=AA(1)-AS(1)
      DA2=AA(2)-AS(2)
      DA3=AA(3)-AS(3)
C
      DD1=DWNA(1)-DWNS(1)
      DD2=DWNA(2)-DWNS(2)
      DD3=DWNA(3)-DWNS(3)
C
      DW=SQRT(DW1*DW1+DW2*DW2+DW3*DW3)
      DA=SQRT(DA1*DA1+DA2*DA2+DA3*DA3)
      DD=SQRT(DD1*DD1+DD2*DD2+DD3*DD3)
C
      AWA=SQRT(WA(1)*WA(1)+WA(2)*WA(2)+WA(3)*WA(3))
      AAA=SQRT(AA(1)*AA(1)+AA(2)*AA(2)+AA(3)*AA(3))
C
      CW=DW/AMAX1(AWA,WTH)
      CA=DA/AMAX1(AAA,ATH)
      CD=DD
C
      CWAV=CWAV+CW
      CAAV=CAAV+CA
      CDAV=CDAV+CD
C
      CWRMS=CWRMS+CW*CW
```

```
      CARMS=CARMS+CA*CA
      CDRMS=CDRMS+CD*CD
C
      ADW=ADW+DW
      ADA=ADA+DA
      ADD=ADD+DD
C
40    CONTINUE
C
      CWAV=CWAV/NSA
      CAAV=CAAV/NSA
      CDAV=CDAV/NSA
      CAVG=CWAV+CAAV+CDAV
C
      CWRMS=SQRT(CWRMS/NSA)
      CARMS=SQRT(CARMS/NSA)
      CDRMS=SQRT(CDRMS/NSA)
      CRMS=CWRMS+CARMS+CDRMS
C
      ADW=ADW/NSA
      ADA=ADA/NSA
      ADD=ADD/NSA
      CAD=ADW+ADA+ADD
C
      WRITE(6,70) ADW,ADA,ADD,CAD
70    FORMAT(//'     ADW=',F11.6,'  ADA=',F11.6,'  ADD='
     *,F11.6,'   TOTAL=',F10.6)
      WRITE(6,50)CWAV,CAAV,CDAV,CAVG
50    FORMAT(/'    CWAV=',F10.6,'  CAAV=',F10.6,'  CDAV='
     *, F10.6,'   TOTAL=',F10.6)
      WRITE(6,60)CWRMS,CARMS,CDRMS,CRMS
60    FORMAT(/'    CWRMS=',F9.6,'  CARMS=',F9.6,'  CDRMS='
     *,F9.6,'   TOTAL=',F10.6/)
30    FORMAT(F6.3,I4)
10    FORMAT(9E14.7)
C
      RETURN
      END
```

```
C   SUBROUTINE TO DIFFERENTIATE THE TIME SERIES
C   CONSISTING OF THE ROTATIONAL POSITION
C   COMMANDS FROM THE DRIVE PROGRAM
C
      SUBROUTINE DIFF(DT,Y,YD,NSP,N)
C
      DIMENSION Y(N,3),YD(N,3)
      DO 10 I=1,NSP
      DO 40 J=1,3
      IF(I-1)20,20,50
50    IF(I-NSP)60,30,30
20    YD(I,J)=(Y(I+1,J)-Y(I,J))/DT
      GO TO 40
30    YD(I,J)=(Y(I,J)-Y(I-1,J))/DT
      GO TO 40
60    YD(I,J)=(Y(I+1,J)-Y(I-1,J))/(2.*DT)
40    CONTINUE
10    CONTINUE
C
      RETURN
      END


C   SUBROUTINE TO TRANSFORM THE COORDINATE SYSTEM OF A VECTOR
C
      SUBROUTINE COTRN(A,B,N,C)
C
C   COORDINATE TRANSFORM:
C
C     FROM HEAD TO SENSOR IF N=0 (DIRECT TRANSFORMATION)
C     FROM SENSOR TO HEAD IF N=-1 (INVERSE TRANSFORMATION)
C     FROM SENSOR TO HEAD IF N=1 (INVERSE TRANSFORMATION
C     USING THE TRANSPOSE FOR ORTHOGONAL MATRICES)
C
C     A=ORIGINAL VECTOR
C     B=TRANSFORMATION MATRIX
C     C=TRANSFORMED VECTOR
C
      DIMENSION A(3),B(3,3),C(3),BI(3,3),L(3),M(3)
C
      IF(N)20,10,30
C
10    DO 15 I=1,3
      C(I)=B(I,1)*A(1)+B(I,2)*A(2)+B(I,3)*A(3)
15    CONTINUE
      RETURN
C
20    CALL MCPY(B,BI,3,3,0)
      CALL MINV(BI,3,D,L,M)
      DO 35 I=1,3
      C(I)=BI(I,1)*A(1)+BI(I,2)*A(2)+BI(I,3)*A(3)
35    CONTINUE
      RETURN
C
30    DO 40 I=1,3
      C(I)=B(1,I)*A(1)+B(2,I)*A(2)+B(3,I)*A(3)
40    CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE EULER(F,T,S,CT)
C
C   PRODUCE DIRECTION COSINE MATRIX (CT) GIVEN EULER ANGLES
C   (F,T, AND S)
C
      DIMENSION CT(3,3)
      CT(1,1)=COS(S)*COS(F)-COS(T)*SIN(F)*SIN(S)
      CT(2,1)=-(SIN(S)*COS(F)+COS(T)*SIN(F)*COS(S))
      CT(3,1)=SIN(T)*SIN(F)
      CT(1,2)=COS(S)*SIN(F)+COS(T)*COS(F)*SIN(S)
      CT(2,2)=COS(T)*COS(F)*COS(S)-SIN(S)*SIN(F)
      CT(3,2)=-SIN(T)*COS(F)
      CT(1,3)=SIN(T)*SIN(S)
      CT(2,3)=SIN(T)*COS(S)
      CT(3,3)=COS(T)
C
      RETURN
      END



      SUBROUTINE CROSS (A,B,C)
C
C    C = A X B
C
      DIMENSION A(3),B(3),C(3)
      C(1)=A(2)*B(3)-A(3)*B(2)
      C(2)=A(3)*B(1)-A(1)*B(3)
      C(3)=A(1)*B(2)-A(2)*B(1)
C
      RETURN
      END



      SUBROUTINE VANG(A,B,PHI)
C
C   PHI = ANGLE BETWEEN A AND B.
C
      DIMENSION A(3),B(3),AN(3),BN(3)
      CALL NORM(A,AN)
      CALL NORM(B,BN)
      PHI=ARCOS(AN(1)*BN(1)+AN(2)*BN(2)+AN(3)*BN(3))
C
      RETURN
      END



      SUBROUTINE NORM(A,AN)
C
C   AN = UNIT VECTOR IN DIRECTION OF VECTOR A.
C
      DIMENSION A(3),AN(3)
      AM=SQRT(A(1)*A(1)+A(2)*A(2)+A(3)*A(3))
      IF(AM-1.E-06) 5,5,6
    5 AM=1.E-06
    6 DO 10 I=1,3
   10 AN(I)=A(I)/AM
C
      RETURN
      END
```

```
      SUBROUTINE SVUPD(X,T,D,S,Y,C,N,M)
C
C   STATE VECTOR UPDATE:
C
C    X(NEW) =T*X(OLD) + D*S
C    Y(NEW) = C*X(NEW)
C
C      WHERE: N IS DIMENSION OF STATE VECTOR
C             X IS STATE VECTOR
C             T IS TRANSITION MATRIX
C             D IS DRIVING VECTOR
C             S IS STIMULUS
C             Y IS OUTPUT (AFFERENT FIRING RATE)
C
      DIMENSION X(N),T(N,N),D(N),C(M),R(9)
      DO 5 I=1,N
    5 R(I)=X(I)
      DO 10 I=1,N
      X(I)=D(I)*S
      DO 10 J=1,N
   10 X(I)=X(I)+T(I,J)*R(J)
      Y=C(M)*S
      DO 20 I=1,N
   20 Y=Y+C(I)*X(I)
C
      RETURN
      END


      SUBROUTINE SSKF(XH,Y,TM,C,GK,N)
C
C   STEADY STATE KALMAN FILTER (UPDATE EVERY DT SECONDS)
C
C      WHERE: XH IS STATE VECTOR ESTIMATE
C             TM IS TRANSITION MATRIX
C             GK IS KALMAN GAIN MATRIX
C             Y IS SENSOR SYSTEM OUTPUT
C             C IS OUTPUT MATRIX
C
      DIMENSION XH(N),TM(N,N),C(N),GK(N),S(9)
      DO 40 I=1,N
      S(I)=0.0
      DO 40 J=1,N
   40 S(I)=S(I)+TM(I,J)*XH(J)
      EM=0.0
      DO 45 I=1,N
   45 EM=EM+S(I)*C(I)
      DO 50 J=1,N
   50 XH(J)=S(J)+GK(J)*(Y-EM)
C
      RETURN
      END


      SUBROUTINE ROTATE (A,R,AR)
C
C   AR = A ROTATED ABOUT R BY ANGLE (RAD) EQUAL TO THE
C   MAGNITUDE OF R
C
      DIMENSION A(3),R(3),AR(3),AP(3),APN(3)
      CALL CROSS (R,A,AP)
      CALL NORM (AP,APN)
      AMAG=SQRT(A(1)*A(1)+A(2)*A(2)+A(3)*A(3))
      PHI=SQRT(R(1)*R(1)+R(2)*R(2)+R(3)*R(3))
      DO 10 I=1,3
   10 AR(I)=AMAG*SIN(PHI)*APN(I)+COS(PHI)*A(I)
C
      RETURN
      END
```

LIST OF REFERENCES

1 Department of the Navy, OPNAV Instruction 3710.7G, CH-1 of 15 May 1973, Natops General Flight and Operating Instructions Manual, 1 January 1973

2 Subcommittee on Research and Development of the Committee on Armed Services United States Senate, Flight Simulators, 13 May 1976

3 Air Force Human Resources Laboratory TR-75-3, ASUPT Automated Objective Performance Measurement System, by W.L. Waag, E.E. Eddowes, J.H. Fuller Jr., R.R. Fuller

4 Shepered, G., Research into the Training Effectiveness of a Full Mission Flight Simulator, paper presented at the AGARD conference on Flight Simulation/Guidance Systems Simulation, The Hague, The Netherlands, 20-23 October 1975

5 Evans, C.L. LT USN, "A (Computer Generated) Picture Is Worth 1000 Words", Approach, v. 21, no. 10, p. 10-11, April 1976

6 Spitzer, R.E., Use of Flight Simulators in YC-14 Design, paper presented at the AGARD conference on Flight Simulation/Guidance Systems Simulation, The Hague, The Netherlands, 20-23 October 1975

7 Fortenbaugh, R.L. and Rebel, J.M., Application of Flight Simulation to Develop, Test, and Evaluate the F-14A Automatic Carrier Landing System, paper presented at the AGARD conference on Flight Simulation/Guidance Systems Simulation, The Hague, The Netherlands, 20-23 October 1975

8 National Transportation Safety Board, Sharp Wind Changes Encountered by 727, Aviation Week and Space Technology, v. 105, no. 2, p. 61-67, 12 July 1976

9 Tuomela, C.H. Captain USN, The Role of the Flight Simulator in Aviation Safety, Flight Simulator Conference, Naval Postgraduate School, Monterey, California, 18-19 September 1975

10 Systems Technology Inc., Technical Report No. 168-1, Dynamics of the Vestibular System and their Relation to Motion Perception, by R.A. Peters, 1968

11 Ormsby, C.C., Model of Human Dynamic Orientation, Ph.D. Thesis, Massachusetts Institute of Technology, 1974

12 Massachusetts Institute of Technology, NASA-CR-149667 Integration of Visual and Motion Cues for Simulator Requirements and Ride Quality Investigation, Semiannual Progress Report, June-December 1976, by L.R. Young

13 Massachusetts Institute of Technology, NASA-CR-148479 Integration of Visual and Motion Cues for Simulator Requirements and Ride Quality Investigation, Semiannual Progress Report, December 1975-June 1976, by L.R. Young

14 NASA Ames Research Center, NASA-CR-2312, Quasi-Optimum Design of a Six Degree of Freedom Simulator Control System, by B. Friedland, C. Ling, and M.F. Hutton, October 1973

15 NASA Ames Research Center, NASA-CR-1601, Motion Drive Signals for Piloted Flight Simulators, by S.F. Schmidt and B. Conrad, May 1970

16 NASA Edwards Flight Research Center, NASA-D-5358, Fixed-Base Simulator Pilot Rating Surveys for Predicting Lateral-Directional Handling Qualities and Pilot Rating Variability, by L.W. Taylor and K.W. Iliff, August 1969

17 Madill, D.R., Simulation: An Introduction and Survey, paper presented at the AGARD conference on Human Factors in Aircraft Simulation, NASA Ames Research Center, 10-13 March 1970

18 Siegel, S., Non-Parametric Statistics, p. 166-172, McGraw-Hill, 1956

19 Duncan, D.B., "Multiple Range and Multiple F tests," Biometrics, v. 11, no. 1, p. 1-42, March 1955

20 Kramer, C.Y., "Extension of Multiple Ringe Tests to Groups with Unequal Numbers of Replications," Biometrics, v. 12, no. 3, p. 307-310, September 1956

21 Borah, J.D., Human Dynamic Orientation Model Applied to Motion Simulation, Master's Thesis, Massachusetts Institute of Technology, 1976

22 Hewett, M.D. and Galloway, R.T., On Improving the Flight Fidelity of Operational Flight/Weapon System Trainers, paper presented at the AGARD conference on Flight Simulation/Guidance Systems Simulation, The Hague, The Netherlands, 20-23 October 1975

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 55 Department of Operations Research and Administrative Sciences Naval Postgraduate School Monterey, California 93940	1
4.	Professor G. K. Poock, Code 55Pk Department of Operations Research and Administrative Sciences Naval Postgraduate School Monterey, California 93940	1
5.	Asst Professor L. E. Waldeisen, Code 55Wd Department of Operations Research and Administrative Sciences Naval Postgraduate School Monterey, California 93940	1
6.	Dr. David C. Nagel N239-2 National Aeronautics and Space Administration, Ames Research Center Moffett Field, California 94035	1
7.	Dr. Laurence R. Young Department of Aeronautics and Astronautics School of Engineering, 37-207 Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1
8.	E. Gene Lyman, Code RB Director, Aeronautical Man-Vehicle Technology Division National Aeronautics and Space Administration Washington, D.C. 20546	1
9.	LT Richard G. Fuller, USN 929 Amherst Lane Virginia Beach, Virginia 23462	1

10. LCDR J. H. Cyr, USN, Code 30 2
Naval Postgraduate School
Monterey, California 93940

Thesis 172329
F9313 Fuller
c.1 An evaluation of the fidelity of motion simulators using a model of human dynamic orientation.